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CONTENTS.

MEETING AT NEW YORK, JANUARY 9, 1914.

Sources of Direct-Current for Electrochemical Processes—By F. D. Newbury 1

MEETING AT NEW YORK, FEBRUARY 25 TO 27, 1914.

Protective Reactance in Large Power Stations—By James Lyman, Allen M. Rossman and Leslie L. Perry. (*Illustrated.*) 23

Outdoor vs. Indoor Substations—By Alexander Macomber 57

Outdoor Substations in New England—By Fred L. Hunt. (*Illustrated.*) 65

Indoor and Outdoor Substations in Pennsylvania—By H. L. Fullerton. (*Illustrated.*) 71

Outdoor Substations in the Middle West—By Leslie L. Perry. (*Illustrated.*) 89

Problems of High-Tension Transmission Lines—Report of Sub-Committee on Transmission—P. W. Sothman, Chairman 105

Practical Operation of Suspension Insulators—By H. W. Buck. (*Illustrated.*) 131

The Economical Capacity of a Combined Hydroelectric and Steam Power Plant—By Cary T. Hutchinson. (*Illustrated.*) 155

The Cost of Electricity at the Source—By H. M. Hobart. (*Illustrated.*) 193

Distribution of Electrical Energy—Report of Sub-Committee on Distribution—P. Junkersfeld, Chairman 211

Recording Devices—By Charles P. Steinmetz. (*Illustrated.*) 283

The Present Status of Aluminum-Cell Lightning Arresters—By E. E. F. Creighton 293

MEETING AT NEW YORK, MARCH 13, 1914.

Traffic Studies in Automatic-Switchboard Telephone Systems—By W. Lee Campbell. (*Illustrated.*) 309

A Comparison of the Telegraph with the Telephone as a Means of Communication in Steam Railroad Operation—By M. H. Clapp 319

MEETING AT CLEVELAND, MARCH 23, 1914.

Sixty-Cycle Synchronous Converters—By L. P. Crecelius 353

MEETING AT PITTSBURGH, APRIL 9 TO 10, 1914.

Mine Duty Controllers—By Harrison P. Reed. (*Illustrated.*) 367

Self Contained Portable Electric Mine Lamps—By H. O. Swoboda. (*Illustrated.*) 385

The Development of the Electric Mine Locomotive—By G. M. Eaton. (*Illustrated.*) 403

Mine Substations—Motor Generator Sets vs. Synchronous Converters—By Will M. Hoen. (*Illustrated.*) 431

Mine Substations—Their Construction and Operation—By H. Booker 439

MEETING AT URBANA, APRIL 16, 1914.

Magnetic and Other Properties of Electrolytic Iron Melted in Vacuo—By Trygve D. Yensen. (*Illustrated.*) 451

MEETING AT WASHINGTON, D.C., APRIL 24 AND 25, 1915.

Solenoids—By Charles R. Underhill. (*Illustrated.*) 477

Some Investigations on Lightning Protection for Buildings—By L. A. De Blois. (*Illustrated.*) 519
Some Simple Examples of Transmission Line Surges—By W. S. Franklin. (*Illustrated.*) 545
A Milliampere Current Transformer—By Edward Bennett. (*Illustrated.*) 571
Theory of the Corona—By Bergen Davis. (*Illustrated.*) 589

MEETING AT NEW YORK, MAY 19, 1914.

Electricity the Future Power for Steering Vessels—By H. L. Hibbard. (*Illustrated.*) 619
The Future of Electric Heating and Cooking in Marine Service—By H. J. Mauger. (*Illustrated.*) 659

MEETING AT SEATTLE, MAY 19, 1914.

Effect of Electrolysis on the Compressive Strength of Cement and Concrete—By C. Edward Magnusson and B. Izhuroff. (*Illustrated.*) 673

MEETING AT PITTSFIELD, MAY 28 AND 29, 1914.

Experiences with Line Transformers—By D. W. Roper. (*Illustrated.*) 685
Inherent Voltage Relations in Y and Delta Connections—By Royal W. Sorensen and Walter L. Newton. (*Illustrated.*) 711
Harmonic Voltages and Currents in Y and Delta Connected Transformers—By R. C. Clinker. (*Illustrated.*) 723
Influence of Transformer Connections on Operation—By Louis F. Blume. (*Illustrated.*) 735
A Study of Some Three Phase Systems—By Charles Fortescue. (*Illustrated.*) 753
Experience of the Pacific Gas and Electric Company with the Grounded Neutral—By J. P. Jollyman, P. M. Downing and F. G. Baum 767
Relative Merits of Y and Delta Connection for Alternators—By T. S. Eden. (*Illustrated.*) 803
Delta and Y Connections for Railway Transmission and Distribution—By Cassius M. Davis 807

MEETING AT DETROIT, JUNE 22 TO 26, 1914.

The Evolution of the Institute and of Its Members—President's Address—By C. O. Mailloux 819
Electric Heating as Applied to Marine Service—By C. S. McDowell and D. M. Mahood. (*Illustrated.*) 839
The Electrically Driven Gyroscope in Marine Work—By H. C. Ford. (*Illustrated.*) 857
Direct-Current Motors for Coal and Ore Bridges—By R. H. McLain. (*Illustrated.*) 873
Methods of Keeping Down Peaks on Power Purchased on a Peak Basis—By T. E. Tynes. (*Illustrated.*) 887
Concatenated Induction Motors for Rolling Mill Drive—By William O. Oschman. (*Illustrated.*) 899
The Sphere Gap as a Means of Measuring High Voltage—By F. W. Peek, Jr. (*Illustrated.*) 923
The Electric Strength of Air—V—By J. B. Whitehead and W. S. Gorton. (*Illustrated.*) 951
Sphere Gap Discharge Voltages at High Frequencies—By J. Cameron Clark and Harris J. Ryan. (*Illustrated.*) 973

CONTENTS

MEETING AT DETROIT, MICH., JUNE 22 TO 26, 1914. (*Continued*).

Engineering Data Relating to High-Tension Transmission Systems—Sub-Committee Report Prepared by the Chairman (*Illustrated*) 1013
Provisional Specification for Insulator Testing—Covering Inspection and Tests of High-Tension Line Insulators of Porcelain, for Over 25,000 Volts 1107
Present Status of Prime Movers—By H. G. Stott, R. J. S. Pigott and W. S. Gorsuch. (*Illustrated.*) 1133
Voltage Testing of Cables—By W. I. Middleton and Chester L. Dawes. (*Illustrated.*) 1185
Sterilization of Water by Ultra-Violet Rays of the Mercury-Vapor Quartz Lamp—By M. von Recklinghausen. (*Illustrated.*) 1217
A High-Speed Printing Telegraph System—By Carl Kinsley. (*Illustrated.*) 1243
Toll Telephone Traffic—An Experimental Study of the Relationship between Circuit Loads and Delay to Traffic—By Frank F. Fowle. (*Illustrated*) 1263

MEETING AT SPOKANE, WASH., SEPTEMBER 9-11, 1914.

The Effect of Delta and Star Connections Upon Transformer Wave Forms—By Leslie F. Curtis. (*Illustrated.*) 1273
150,000-Volt Transmission System—Some Operating Conditions of the Big Creek Development of the Pacific Light and Power Corporation—By Edward Woodbury. (*Illustrated.*) 1283
A Distribution System for Power Purposes—By F. D. Nims. (*Illustrated.*) 1299
Electricity in the Lumber Industry—By E. F. Whitney. (*Illustrated.*) 1315
The Electrical Operation of the Butte, Anaconda and Pacific Railway—By J. B. Cox. (*Illustrated.*) 1369
Application of Electric Motors to Gold Dredges—By Girard B. Rosenblatt. (*Illustrated.*) 1405
Economy in the Operation of 55,000-Volt Insulators—By M. T. Crawford. (*Illustrated.*) 1429
Report by the Joint Committee on Inductive Interference to the Railroad Commission of the State of California 1441

MEETING AT NEW YORK, OCTOBER 9, 1914.

Protective Reactors for Feeder Circuits of Large City Power Systems—By James Lyman, Leslie L. Perry and A. M. Rossman. (*Illustrated.*) 1509
Use of Reactance with Synchronous Converters—An Insurance to Continuity of Service and a Protection to Apparatus—By J. L. McK. Yardley .. (*Illustrated.*) 1521

MEETING AT PHILADELPHIA, PA., OCTOBER 12, 1914

Submarine Signaling—The Protection of Shipping by a Wall of Sound and Other Uses of the Submarine Telegraph Oscillator—By R. F. Blake. (*Illustrated.*) 1549

Electrical Equipment of the Argentine Battleship "Moreno"—By H. A. Hornor. (*Illustrated.*) 1567
Electrical Features of the U. S. Reclamation Service—By F. H. Newell 1609

MEETING AT NEW YORK, NOVEMBER 13, 1914.

The Corona Produced by Continuous Potentials—By Stanley P. Farwell. (*Illustrated.*) 1631
Graphic Method for Speed-Time and Distance-Time Curves—By E. C. Woodruff. (*Illustrated.*) 1673

MEETING AT NEW YORK, DECEMBER 11, 1914.

Effect of Altitude on the Spark-Over Voltages of Bushings, Leads and Insulators—By F. W. Peek, Jr. (*Illustrated.*) 1721
Insulator Depreciation and Effect on Operation—By A. O. Austin. (*Illustrated.*) 1731

Specification and Analytical Procedure for 30 Per Cent Hevea Rubber Insulating Compound 1767
Standardization Rules of the American Institute of Electrical Engineers 1787
Report of Board of Directors for Fiscal Year Ending April 30, 1914 .. 1895

Index of Papers and Discussions v
Index of Authors vi
Synoptical and Topical Index ..... End of Part II

INDEX

Note: For complete topical and synoptical index see end of Part II.

PAPERS AND DISCUSSIONS

Comparison of the Telegraph with the Telephone as a Means of Communication in Steam Railroad Operation. (*M. H. Clapp.*) 319

Concatenated Induction Motors for Rolling Mill Drive. (Illustrated.) (*William O. Oschman.*) 899

Cost of Electricity at the Source, The. (Illustrated.) (*H. M. Hobart.*) 193

Delta and Y Connections for Railway Transmission and Distribution. (*Cassius M. Davis.*) 807

Development of the Electric Mine Locomotive. (Illustrated.) (*G. M. Eaton.*) 403

Direct-Current Motors for Coal and Ore Bridges. (Illustrated.) (*R. H. McLain.*) 873

Distribution of Electrical Energy. Report of Sub-Committee on Distribution. (*P. Junkersfeld, Chairman.*) 211

Economical Capacity of a Combined Hydro-Electric and Steam Power Plant. (Illustrated.) (*Cary T. Hutchinson.*) 155

Effect of Electrolysis on the Compressive Strength of Cement and Concrete. (Illustrated.) (*C. Edward Magnusson and B. Ishuroff.*) 673

Electric Heating as Applied to Marine Service. (Illustrated.) (*C. S. McDowell and D. M. Mahood.*) 839

Electric Strength of Air—V, The. (Illustrated.) *J. B. Whitehead and W. S. Gorton.*) 951

Electrically Driven Gyroscope in Marine Work ,The. (Illustrated.) (*H. C. Ford.*) 857

Electricity the Future Power for Steering Vessels. (Illustrated.) (*H. L. Hibbard.*) 619

Evolution of the Institute and of Its Members, The. President's Address. (*C. O. Mailloux.*) 819

Experience of the Pacific Gas and Electric Company with the Grounded Neutral. (*J. P. Jollyman, P. M. Downing and F. G. Baum.*) 767

Experiences with Line Transformers. (Illustrated.) (*D. W. Roper.*) 685

Future of Electric Heating and Cooking in Marine Service, The. (Illustrated.) (*H. J. Mauger.*) 659

Harmonic Voltages and Currents in Y and Delta-Connected Transformers. (Illustrated.) (*R. C. Clinker.*) 723

Indoor and Outdoor Substations in Pennsylvania. (Illustrated.) (*H. L. Fullerton.*) 71

Influence of Transformer Connections on Operation. (Illustrated.) (*Louis F. Blume.*) 735

Inherent Voltage Relations in Y and Delta Connections. (Illustrated.) (*Royal W. Sorensen and Walter L. Newton.*) 711

Magnetic and Other Properties of Electrolytic Iron Melted in Vacuo. (Illustrated.) (*Trygve D. Yensen.*) 451

Methods of Keeping Down Peaks on Power Purchased on a Peak Basis. (Illustrated.) (*T. E. Tynes.*) 887

Milliampere Current Transformer, A. (Illustrated.) (*Edward Bennett.*) 571
Mine Duty Controllers. (Illustrated.) (*Harrison P. Reed.*) 367
Mine Substations—Motor-Generator Sets vs. Synchronous Converters. (Illustrated.) (*Will M. Hoen.*) 431
Mine Substations—Their Construction and Operation. (*H. Booker.*) 439
Outdoor Substations in New England. (Illustrated.) (*Fred L. Hunt.*) 65
Outdoor Substations in the Middle West. (Illustrated.) (*Leslie L. Perry.*) 89
Outdoor vs. Indoor Substations. (*Alexander Macomber.*) 57
Practical Operation of Suspension Insulators. (Illustrated.) (*H. W. Buck.*) 131
Present Status of Aluminum-Cell Lightning Arresters. (*E. E. F. Creighton.*) 293
Problems of High-Tension Transmission Lines—Report of Sub-Committee on Transmission. (*P. W. Sothman, Chairman.*) 105
Protective Reactance in Large Power Stations. (Illustrated.) (*James Lyman, Allen M. Rossman and Leslie L. Perry.*) 23
Recording Devices. (Illustrated.) (*Charles P. Steinmetz.*) 283
Relative Merits of Y and Delta Connection for Alternators. (Illustrated.) (*T. S. Eden.*) 803
Self-Contained Portable Electric Mine Lamps. (Illustrated.) (*H. O. Swoboda.*) 385
Sixty-Cycle Synchronous Converters. (*L. P. Crecelius.*) 353
Solenoids. (Illustrated.) (*Charles R. Underhill.*) 477
Some Investigations on Lightning Protection for Buildings. (Illustrated.) (*L. A. De Blois.*) 519
Some Simple Examples of Transmission Line Surges. (Illustrated.) (*W. S. Franklin.*) 545
Sources of Direct Current for Electrochemical Processes. (*F. D. Newbury.*) 1
Sphere Gap as a Means of Measuring High Voltage, The. (Illustrated.) (*F. W. Peek, Jr.*) 923
Sphere Gap Discharge Voltages at High Frequencies. (Illustrated.) (*J. Cameron Clark and Harris J. Ryan.*) 973
Study of Some Three-Phase Systems, A. (Illustrated.) (*Charles Fortescue.*) 753
Theory of the Corona. (Illustrated.) (*Bergen Davis.*) 589
Traffic Studies in Automatic-switchboard Telephone Systems. (Illustrated.) (*W. Lee Campbell.*) 309

INDEX TO AUTHORS

Abell, H. C., Discussion 202
Addicks, Lawrence, Discussion 20, 21
Albrecht, E. R., Discussion 148
Alverson, H. B., Discussion 202, 707
Antisell, F. L., Discussion 15
Argersinger, Roy E., Discussion 95
Averrett, A. E., Discussion 921
Bauhan, Alex. E., Discussion 54
Baum, F. G., Paper 767
Beekman, R. A., Discussion 654
Beers, C. W., Discussion 416
Bennett, Edward, Paper 571; Discussion 587, 609
Bibbins, J. R., Discussion 894
Biesecker, Arthur S., Discussion 383
Blair, E. J., Paper 251
Blume, Louis F., Paper 735; Discussion 731, 785, 797
Booker, H., Paper 439
Brand, F. F., Discussion 775
Bright, Graham, Discussion 378, 420
Brundige, J. A., Paper 119
Buck, H. W., Paper 131; Discussion 138, 151, 201
Burrows, Charles W., Discussion 510
Burrows, R. C., Discussion 399
Bussey, Henson E., Discussion 100
Caldwell, F. C., Discussion 854, 990
Campbell, W. Lee, Paper 309; Discussion 345, 346
Carichoff, E. R., Discussion 514
Carlton, W. G., Paper 259
Chernyshoff, Alex., Discussion 609
Chubb, L. W., Discussion 988
Clapp, M. H., Paper 319; Discussion 345, 349
Clark, H. H., Discussion 379, 397
Clark, J. Cameron, Paper 973
Clarke, Chas. L., Discussion 290
Clinker, R. C., Paper 723
Collbohm, Max H., Discussion 801
Craighead, J. R., Discussion 586, 1000
Crecelius, L. P., Paper 353
Creighton, E. E. F., Paper 293; Discussion 307, 536, 705, 789, 994
Davis, Bergen, Paper 589; Discussion 616
Davis, Cassius M., Paper 807; Discussion 52, 785, 815
Day, Maxwell W., Discussion 652
De Blois, L. A., Paper 519; Discussion 543
Doherty, R. E., Discussion 815
Downing, P. M., Paper 124, 767
Dreyfus, E. D., Discussion 896
Dutton, E. F., Discussion 670
Dwight, H. B., Discussion 996
Eaton, G. M., Paper 403; Discussion 422, 428
Eden, T. S., Paper 803; Discussion 814
Ewing, D. D., Discussion 994
Faccioli, G., Paper 127
Fechheimer, C. J., Discussion 811, 814, 815

Fishel, A. D., Discussion 698
Ford, H. C., Paper 857; Discussion 872
Fortescue, Charles, Paper 753; Discussion 732, 799, 990
Franklin, W. S., Paper 545
Franz, Joseph, Discussion 703
Fullerton, H. L., Paper 71
Gear, H. B., Paper 222; Discussion 95, 280
Goodwin, H., Paper 236
Gorton, W. S., Paper 951
Grace, D. P., Discussion 344
Granger, W. L., Discussion 707
Green, F. C., Discussion 731, 792
Haar, Selby, Discussion 816
Hadaway, W. S., Discussion 669, 851
Hamilton-Ellis, A., Discussion 568
Harkness, William E., Discussion 340
Harlan, O. K., Discussion 202
Harris, F. W., Discussion 22
Haskell, F. E., Discussion 789
Herreshoff, J. B. F., Discussion 15
Herreshoff, J. B., Discussion 16
Hewlett, E. M., Discussion 151, 273
Hibbard, H. L., Paper 619; Discussion 654
Hill, R. N., Discussion 342
Hobart, H. M., Paper 193; Discussion 205
Hoen, Will M., Paper 431; Discussion 382, 448
Hornor, H. A., Discussion 656, 855
Hough, H. W., Discussion 701
Humphreys, W. J., Discussion 541
Hunt, Fred L., Paper 65
Hutchinson, Cary T., Paper 155
Ilsley, L. J., Discussion 422
Izhuroff, B., Paper 673
Jackson, Dugald C., Discussion 102, 732
James, H. D., Discussion 380
Jollyman, J. P., Paper 767
Junkersfeld, P., Paper 211
Karapetoff, V., Discussion 50, 146, 203, 301
Kearns, J. Edward, Discussion 99
Kelly, J. T., Jr., Discussion 278, 279
Kennedy, W. C., Discussion 380, 384
Kennelly, A. E., Discussion 728
Knight, Charles D., Discussion 853
Knight, G. L., Discussion 204
Kouwenhoven, W. B., Discussion 1005
Kruesi, A. H., Discussion 92, 203
Leilich, Frank T., Discussion 671
Lewis, W. W., Discussion 775, 998
Lidbury, F. A., Discussion 13
Lieb, J. W., Jr., Discussion 201
Lincoln, Paul M., Paper 266; Discussion 49, 146, 446, 702, 732, 794, 893
Lindsay, S. C., Discussion 885
Lloyd, M. G., Discussion 1005
Lof, E. A., Discussion 101, 150
Longwell, H. E., Discussion 21
Lyman, James, Paper 23
Lyon, Waldo, V., Discussion 728
Macomber, Alexander, Paper 57
Magnusson, C. Edward, Paper 673
Mahood, D. M., Paper 839; Discussion 855, 990
Mailloux, C. O., Paper 819; Discussion 17, 151, 303, 789
Martindale, E. H., Discussion 426

Mauger, H. J., Paper 659; Discussion 670
Maver, William, Jr., Discussion 339
McClelland, R. J., Discussion 143
McDowell, C. S., Paper 839
McLain, R. H., Paper 873; Discussion 886, 895
McNicol, Donald, Discussion 347
Merriam, E. B., Paper 262
Merrick, E. G., Discussion 813, 815
Miller, W. W., Discussion 415, 423
Montsinger, V. M., Discussion 779
Moody, W. S., Discussion 47, 96, 698
Murphy, John, Discussion 279
Murray, W. S., Paper 261
Newbury, F. D., Paper 1; Discussion 21
Newton, Walter L., Paper 711
Nicholson, L. C., Paper 123; Discussion 302
Olshausen, George R., Discussion 537, 542
Osborne, H. S., Discussion 786, 789
Oschmann, William O., Paper 899
Osgood, Farley, Discussion 102, 147
Pannell, Ernest V., Discussion 149
Peck, E. P., Discussion 1000
Peek, F. W., Jr., Paper 923; Discussion 138, 301, 612, 729, 795, 1000
Pender, Harold, Discussion 728
Perry, Leslie L., Paper 23, 89
Pfatischer, Mathias, Discussion 651
Pierce, G. A., Jr., Discussion 649
Puffer, William L., Discussion 149
Randall, K. C., Discussion 99, 152
Reed, Harrison P., Paper 367
Rice, R. H., Paper 240
Roper, D. W., Paper 685; Discussion 272, 709, 794
Rossman, Allen M., Paper 23; Discussion 52, 97
Roush, G. A., Discussion 13
Rushmore, D. B., Discussion 854, 885
Ryan, Harris J., Paper 973; Discussion 607, 1010
Sandford, J. A., Jr., Discussion 147
Scheffler, Frederick A., Discussion 201
Schwartz, Carl, Discussion 280
Semenza, Guido, Discussion 773
Shapter, G. H., Discussion 425
Smith, A. R., Discussion 92
Smith, H. H., Discussion 398
Smith, J. C., Discussion 98, 150
Sorensen, Royal W., Paper 711
Sothman, P. W., Paper 105; Discussion 98
Sprong, S. D., Discussion 272
Stahl, N., Discussion 446, 448
Steinmetz, Charles P., Paper 283; Discussion 303
Stone, F. L., Discussion 376, 422, 423, 429
Storer, N. W., Discussion 427
Stott, Henry G., Discussion 47
Strong, Frederick G., Discussion 205
Summerhayes, H. R., Discussion 201, 274
Swoboda, H. O., Paper 385; Discussion 401
Taylor, John B., Discussion 275, 345, 790, 811, 816
Thomas, Percy H., Discussion 142
Thomas, W. A., Discussion 423, 445, 448
Thomson, Elihu, Discussion 539
Torchio, Philip, Paper 217; Discussion 46, 272, 275
Trafford, E. W., Discussion 277
Troy, M. O., Discussion 703

Tschentscher, Rudolph, Discussion 893, 921
Tynes, T. E., Paper 887; Discussion 885, 898, 921
Underhill, Charles R., Paper 477; Discussion 516
Vigo, Sidney G., Discussion 378
Vom Baur, C. H., Discussion 20
Waddell, Charles E., Discussion 141
Wallau, H. L., Discussion 201, 270
Waller, Alfred E., Discussion 852, 872
Waxbom, C. J. E., Discussion 382, 420, 423
Webster, A. G., Discussion 538, 567
Weed, J. Murray, Discussion 560, 732
Werth, J. R., Discussion 797
Whitehead, J. B., Paper 951; Discussion 586, 607; 1002
Woodbridge, J. Lester, Discussion 893
Woodrow, Harry R., Discussion 51
Wooldridge, W. J., Discussion 708
Yensen, Trygve D., Paper 451; Discussion 542

INDEX

PAPERS AND DISCUSSIONS

Application of Electric Motors to Gold Dredges. (Illustrated.) *Girard B. Rosenblatt* 1405
Corona Produced by Continuous Potentials, The. (Illustrated.) *Stanley P. Farwell* 1631
Distribution System for Power Purposes, A. (Illustrated.) *F. D. Nims* 1299
Economy in the Operation of 55,000-Volt Insulators. (Illustrated.) *M. T. Crawford* 1429
Effect of Altitude on the Spark-Over Voltages of Bushings, Leads and Insulators. (Illustrated.) *F. W. Peek, Jr* 1721
Effect of Delta and Star Connections upon Transformer Wave Forms. (Illustrated.) *Leslie F. Curtis* 1273
Electrical Equipment of the Argentine Battleship "Moreno," (Illustrated.) *H. A. Hornor* 1567
Electrical Features of the U. S. Reclamation Service. *F. H. Newell* 1609
Electrical Operation of the Butte, Anaconda and Pacific Railway. The. (Illustrated.) *J. B. Cox* 1369
Electricity in the Lumber Industry. (Illustrated.) *E. F. Whitney* 1315
Engineering Data Relating to High-Tension Transmission Systems. (Illustrated.) *P. H. Thomas* 1013
Graphic Method for Speed-Time and Distance-Time Curves. (Illustrated.) *E. C. Woodruff* 1673
High Speed Printing Telegraph System, A. (Illustrated.) *Carl Kinsley* 1243
Insulator Depreciation and Effect on Operation. (Illustrated.) *A. O. Austin* 1731
Present Status of Prime Movers. (Illustrated.) *H. G. Stott, R. J. S. Pigott and W. S. Gorsuch* 1133
Protective Reactors for Feeder Circuits of Large City Power Systems. (Illustrated.) *James Lyman, Leslie L. Perry and A. M. Rossman* 1509
Provisional Specification for Insulator Testing 1107
Report of the Board of Directors for Fiscal Year Ending April 30, 1914 1895
Report by the Joint Committee on Inductive Interference to the Railroad Commission of the State of California 1441
Specification and Analytical Procedure for 30 Per cent Hevea Rubber Insulating Compound 1767
Standardization Rules of the A. I. E. E. 1787
Sterilization of Water by Ultra-Violet Rays of the Mercury-Vapor Quartz Lamp. (Illustrated.) *M. von Recklinghausen* 1217
Submarine Signaling. (Illustrated.) *R. F. Blake* 1549
Toll Telephone Traffic. (Illustrated.) *Frank F. Fowle* 1263
Transmission System, 150,000-Volt. (Illustrated.) *Edward Woodbury* 1283
Use of Reactance with Synchronous Converters. (Illustrated.) *J. L. McK. Yardley* 1521
Voltage Testing of Cables. (Illustrated.) *W. I. Middleton and Chester L. Dawes* 1185

INDEX OF AUTHORS

Akimoff, N. W., Discussion 1696
Argersinger, R. E., Discussion 1097
Armstrong, L. K., Discussion 1422
Austin, A. O., Paper 1731
Babcock, A. H., Discussion 1506
Barfoed, S., Discussion 1177
Bennett, Edward, Discussion 1126
Bibbins, J. R., Discussion 1170
Bierer, B. B., Discussion 1600
Blake, R. F., Paper 1549
Bowie, A. J., Jr., Discussion 1492, 1500
Breed, George, Discussion 1563
Brooks, Morgan, Discussion 1231
Buck, H. W., Discussion 1536
Burnham, Mr., Discussion 1542
Carpenter, H. V., Discussion 1280, 1308, 1310
Castiglioni, F., Discussion 1704
Cheek, Mr., Discussion 1358
Cheney, Edward J., Discussion 1763
Chubb, L. W., Discussion 1667
Cochrane, W. F., Discussion 1602
Corbett, L. J., Discussion 1278, 1309, 1438, 1497
Cornick, T. R., Discussion 1437
Cox, J. B., Paper 1369; Discussion 1397
Craighead, J. R., Discussion 1212
Crawford, M. T., Paper 1429; Discussion 1311
Creighton, E. E. F., Discussion 1094, 1122, 1126, 1211, 1759
Curtis, Harvey L., Discussion 1745
Curtis, Leslie F., Paper, 1273; Discussion 1280
Dawes, Chester L., Paper, 1185; Discussion 1213
Day, Maxwell W., Discussion 1593, 1605
Del Mar, W. A., Discussion 1207
Dreyfus, E. D., Discussion 1173
Eby, E. D., Discussion 1754, 1763
Ewing, D. D., Discussion 1097, 1718
Farwell, Franklin M., Discussion 1179
Farwell, Stanley P., Paper 1631
Fay, H. J. W., Discussion 1562, 1563, 1565
Fechheimer, Carl J., Discussion 1540
Ferris, Livingston P., Discussion 1279
Fisken, John B., Discussion 1090, 1093, 1095, 1129, 1295, 1305, 1357, 1491
Fleming, R., Discussion 1096
Fortescue, Charles L., Discussion 1211
Fowle, Frank F., Paper 1263
Frank, J. J., Discussion 1539
Franklin, W. S., Discussion 1562, 1563, 1565
Fraser, W. H. R., Discussion 1359
Gerry, M. H., Jr., Discussion 1279, 1296, 1297, 1418, 1436, 1439, 1440
Goodwin, H., Jr., Discussion 1627
Gorsuch, W. S., Paper, 1133; Discussion 1182
Greisser, V. H., Discussion 1297, 1436

Haar, Selby, Discussion.....1100, 1668, 1677, 1757
Halloran, A. H., Discussion..... 1491
Hanchett, George T., Discussion..... 1540
Harisberger, J., Discussion.....1295, 1309, 1360, 1435, 1440
Harris, Ford W., Discussion..... 1417
Hering, Carl, Discussion..... 1627
Hewlett, E. M., Discussion..... 1127
Hibbard, H. L., Discussion.....1593, 1599
Hoadley, G. A., Discussion.....1562, 1565
Hobart, H. M., Discussion..... 1172
Hornor, H. A., Paper, 1567; Discussion.....1563, 1607, 1626
Howard, Mr., Discussion..... 1542
Humphrey, Geo. S., Discussion..... 1495
Jackson, R. P., Discussion..... 1765
Jackson, William B., Discussion.....1131, 1232, 1236
Joint Committee on Inductive Interference, Paper, 1441; Discussion..... 1501
Kahler, C. P., Discussion.....1395, 1498
Karapetoff, Vladimir, Discussion..... 1626
Kennelly, A. E., Discussion.....1667, 1669
Kershner, J. E., Discussion..... 1625
Kimball, E. E., Discussion..... 1710
Kinsley, Carl, Paper, 1243; Discussion.....1260, 1261
Lebenbaum, Paul, Discussion.....1310, 1394, 1397
Leisen, Theodore, Discussion..... 1231
Lincoln, P. M., Discussion.1278, 1305, 1308, 1309, 1626, 1627, 1667
Lindsay, S. C., Discussion.....1090, 1129
Linnard, J. H., Discussion..... 1602
Lof, E. A., Discussion..... 1099
Lyman, James, Paper..... 1509
MacCalla, C. S., Discussion..... 1307
Macomber, George S., Discussion..... 1259
Mailloux, C. O., Discussion.....1209, 1677, 1716
Martin, J. C., Discussion..... 1496
McDowell, Clyde S., Discussion..... 1604
Merwin, L. T., Discussion.....1279, 1358, 1438, 1498
Middleton, W. I., Paper, 1185; Discussion..... 1213
Miller, A. A., Discussion.1278, 1296, 1356, 1397, 1425, 1436, 1440
Newell, F. H., Paper, 1609; Discussion..... 1628
Nims, F. D., Paper, 1299; Discussion..... 1311
Noack, H. R., Discussion..... 1436
Norman, A., Discussion..... 1359
Norton, H. H., Discussion..... 1096
Nunn, P. N., Discussion..... 1486
Osgood, Farley, Discussion.....1128, 1131, 1760
Pannell, Ernest V., Discussion..... 1092
Peek, F. W., Jr., Paper, 1721; Discussion.1095, 1097, 1129, 1668, 1669, 1761
Perry, Leslie L., Paper..... 1509
Pierce, G. A., Jr., Discussion..... 1594
Pigott, R. J. S., Paper, 1133; Discussion..... 1182
Pope, Ralph W., Discussion.....1255, 1439, 1625
Porter, L. C., Discussion..... 1606
Ralston, J. C., Discussion..... 1396
Recklinghausen, M. von, Paper, 1217; Discussion... 1096, 1233, 1667
Robinson, E. G., Jr., Discussion..... 1279
Robinson, L. T., Discussion..... 1668
Rogers, C. E., Discussion..... 1500
Rohrbach, F. J., Discussion.....1306, 1310
Rosenblatt, Girard B., Paper, 1405; Discussion.....1309, 1426
Ross, F. A., Discussion..... 1421

Rossman, A. M., Paper 1509
Rushmore, D. B., Discussion 1534, 1754
Schneider, H. H., Discussion 1764
Scott, Mr., Discussion 1355
Shepard, W. M., Discussion 1422
Sothman, P. W., Discussion 1755
Spencer, Paul, Discussion 1625
Sperry, Elmer A., Discussion 1562, 1597
Stacy, W. K., Discussion 1397
Steinmetz, Charles P., Discussion 1757
Sticht, H. H., Discussion 1763
Storer, N. W., Discussion 1539, 1710
Stott, H. G., Paper, 1133; Discussion 1176, 1210
Summerhayes, H. R., Discussion 1538, 1546
Taylor, John B., Discussion 1545, 1563
Thomas, P. H., Paper, 1013; Discussion 1090, 1091, 1093, 1095, 1096, 1120, 1125, 1129, 1131, 1212
Torchio, Philip, Discussion 1535, 1542
Tschentscher, R., Discussion 1167
Underhill, C. R., Discussion 1254, 1260
Walden, A. E., Discussion 1237
Wayne, J. Lloyd, Discussion 1271
Weber, F. D., Discussion 1356, 1360
Whitney, E. F., Paper, 1315; Discussion 1360
Woodbridge, J. L., Discussion 1565
Woodbury, Edward, Paper, 1283; Discussion 1297, 1309, 1310, 1440
Woodruff, E. C., Paper, 1673; Discussion 1716
Woodward, Mr., Discussion 1542
Wynne, F. E., Discussion 1710
Yardley, J. L. McK., Paper, 1521; Discussion 1544

SYNOPTICAL AND TOPICAL

INDEX

OF

A.I.E.E. TRANSACTIONS

Vol. XXXIII, Parts I and II

The main headings under which these synopses are classified were arrived at by a careful study of all the papers contributed since the organization of the Institute.

The method of making this classification may be called the automatic method, since it is created by sorting the papers themselves into groups and then naming the groups.

Many papers fall naturally into several different groups and in such cases they are inserted under as many different heads as it is thought they rightfully belong.

The classified synopses are designed for those searching for comprehensive information on any given topic, while the subject index is intended for those looking up specific and definite data or information.

MAIN SECTIONS OF SYNOPTICAL INDEX

		Page
1.	Education	
2.	General Theory	3
3.	Units, Measurements and Instruments	5
4.	Insulation and Dielectric Phenomena	7
5.	Electric Conductors	10
6.	Magnetic Properties and Testing of Iron	12
7.	Batteries	12
8.	Transformers	12
9.	Electrical Machinery and Apparatus	15
10.	Prime Movers and Steam Boilers	17
11.	Power Plants and Central Stations	18
12.	Parallel Operation	
13.	Transmission Lines	19
14.	Electric Service Disturbances and Protection	24
15.	Distribution Systems	26
16.	Control, Regulation and Switching	28
17.	Traction	30
18.	Lighting and Lamps	33
19.	Electricity in the Army and Navy	33
20.	Miscellaneous Applications of Electricity	34
21.	Telephony and Telegraphy	38
22.	Miscellaneous Topics and Institute Affairs	40

2. GENERAL THEORY

SOLENOIDS

By Charles R. Underhill **Vol. xxxiii—1914, pp. 477-509**

Fundamental equation for design of solenoids and plunger magnets. Tables and curves giving constants for use in formulas. Characteristic curves of actual solenoids and plunger magnets.

Discussion, pages 510-517, by Messrs. Charles W. Burrows, E. R. Carichoff and C. R. Underhill.

Equations for magnetic field of solenoids.

SOME INVESTIGATIONS ON LIGHTNING PROTECTION FOR BUILDINGS

L. A. DeBlois **Vol. xxxiii—1914, pp. 519-535**

Description of investigations conducted for a large manufacturer of explosives to determine upon a suitable system of lightning protection for buildings containing explosives.

An analysis by oscillograph of the secondary currents induced by actual lightning discharges in vertical earthed conductors. Tentative explanation of the phenomena generally attributed to high frequency oscillations by the existence of unidirectional waves of almost vertical front.

An investigation of the primary effects of a 20-in. spark in air having the same essential characteristics as those attributed to lightning when applied to a model protective system consisting of isolated vertical conductors surrounding a small building.

An investigation of the secondary effects produced under the above conditions.

Brief description of a general protective system recommended for explosives buildings.

Discussion, pages 536-544, by Messrs. E. E. F. Creighton, George R. Olshausen, A. G. Webster, Elihu Thomson, W. J. Humphreys, Trygve D. Yensen and L. A. DeBlois.

Remarks on the nature of lightning and lightning strokes.

SOME SIMPLE EXAMPLES OF TRANSMISSION LINE SURGES

W. S. Franklin **Vol. xxxiii—1914, pp. 545-559**

Analytical discussion of waves produced in transmission lines by surging. The ribbon wave and practical examples of its application.

Discussion, pages 560-569, by Messrs. J. Murray Weed, A. G. Webster and A. Hamilton-Ellis.

Mathematical analysis of transmission line performance under surging conditions.

THEORY OF THE CORONA

Bergen Davis **Vol. xxxiii—1914, pp. 589-606**

Development of a theory of corona, the laws of which are based upon known principles of the motions of ions and ionization by impact.

Discussion, pages 607-617, by Messrs. J. B. Whitehead, Harris J. Ryan, Edward Bennett, Alex. Chernyshoff, F. W. Peek, Jr. and Bergen Davis.

Influence of electric field upon the molecules in decreasing the energy required for ionization. Manner in which Peek's law of visual corona was derived.

THE SPHERE GAP AS A MEANS OF MEASURING HIGH VOLTAGE

F. W. Peek, Jr. **Vol. xxxiii—1914, pp. 923-949**

Disadvantages of needle gap and advantages of sphere gap, in the measurement of high voltage. Deduction of laws for sphere gap with variations in air density. Equations for calculating sphere gap spark-over curves for various spacings, radii, air density, etc. Standard measured curves for convenient sizes of spheres at sea level with table for applying curves to any altitude. Discussion of effect of high frequency and impulse voltages. Precautions necessary in high voltage measurements with test results.

Discussion incorporated with that of paper by J. Cameron Clark and Harris J. Ryan on "Sphere Gap Discharge Voltages at High Frequencies."

THE ELECTRIC STRENGTH OF AIR—V.
The Influence of Frequency

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General discussion of methods and precautions in measuring extremely high e.m.fs. Description of experiments with conductor near absolute zero of temperature, showing electrical resistance to be practically zero.

THE CORONA PRODUCED BY CONTINUOUS POTENTIALS

Stanley P. Farwell **Vol. xxxiii—1914, pp. 1631-1666**

Experimental investigation of the corona around small wires as produced by continuous potentials up to 15,000 volts, obtained from a series of 500-volt generators.

The wire and coaxial cylinder method was employed for a number of experiments. Critical voltages and characteristic potential difference

and current curves for different sized wires. The effect of pressure upon appearance of corona, critical voltage, and current. Characteristic curves of the effect of varying pressure, moisture and temperature.

Discussion, pages 1667-1671, by Messrs. L. W. Chubb, A.E. Kennelly, P. M. Lincoln, Max von Recklinghausen, L. T. Robinson, Selby Haar, F. W. Peek, Jr., A. E. Kennelly and S. P. Farwell.

Comparison of a-c. with d-c. corona losses.

3. MEASUREMENTS AND INSTRUMENTS

RECORDING DEVICES

Charles P. Steinmetz **Vol. xxxiii—1914, pp. 283-292**

Fundamental types of automatic recorders. Demonstration by practical examples of usefulness of automatic recorders in operation of electric systems. Use of multi-recorder.

No discussion.

TRAFFIC STUDIES IN AUTOMATIC-SWITCHBOARD TELEPHONE SYSTEMS

W. Lee Campbell **Vol. xxxiii—1914, pp. 309-318**

Methods of observing traffic. Description of traffic-recording machine. Relative efficiency of trunk groups as shown by traffic recorder. Study of loads and determination of grouping of trunks. Charts and equations.

Discussion incorporated with that of paper by M. H. Clapp on "A Comparison of the Telegraph with the Telephone as a Means of Communication in Steam Railroad Operation."

A MILLIAMPERE CURRENT TRANSFORMER

Edward Bennett **Vol. xxxiii—1914, pp. 571-586**

The drawing and specification for a transformer for use with oscillograph for measuring current of a single insulator or a few feet of high-tension transmission line.

The transformer relations are discussed; the methods of determining the transformer constants are outlined and the performance of transformers constructed in accordance with the specifications is determined.

A series of oscillograms is given to illustrate some of the applications of the transformer, such as to the study of corona, high-tension insulators, and leakage currents in evacuated lamps.

Discussion, pages 586-588, by Messrs. J. B. Whitehead, J. R. Craighead and Edward Bennett.

Criticisms of paper.

METHODS OF KEEPING DOWN PEAKS ON POWER PURCHASED ON A PEAK BASIS

T. E. Tynes **Vol. xxxiii—1914, pp. 887-892**

Brief statement of two general ways of reducing peaks followed by description of a special peak-taking device.

Discussion, pages 893-898, by Messrs. Rudolph Tschentscher, Paul M. Lincoln, J. Lester Woodbridge, J. R. Bibbins, R. H. McLain, E. D. Dreyfus and T. E. Tynes.

General remarks on automatic peak absorption. Discussion of the economic expediency of absorbing peaks as against straight purchase of energy.

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VOLTAGE TESTING OF CABLES

W. I. Middleton and Chester L. Dawes **Vol. xxxiii—1914, pp. 1185-1206**

Analysis of e. m. f. stresses in insulation. Tests that must be made, followed by description of new type of oscillating voltmeter for measuring peak values.

Discussion, pages 1207-1215, by Messrs. W. A. Del Mar, C. O. Mailloux, Henry G. Stott, E. E. F. Creighton, Charles L. Fortescue, Percy H. Thomas, J. R. Craighead, W. I. Middleton, and Chester L. Dawes.

General remarks on voltage testing of cables—what voltage, what sources. Cause of third harmonic disturbances and effect of peak e. m. f.

GRAPHIC METHOD FOR SPEED-TIME AND DISTANCE-TIME CURVES

E. C. Woodruff **Vol. xxxiii—1914, pp. 1673-1676**

Description of a simple method for obtaining speed-time and distance-time curves which avoids the usual step-by-step process.

Discussion, pages 1677-1719, by Messrs. Selby Haar, C. O. Mailloux, N. W. Akimoff, F. Castiglioni, F. E. Wynne, N. W. Storer, E. C. Woodruff and D. D. Ewing.

Résumé of the Mailloux method of calculating and plotting speed-time curves and comparison with the author's method. Equation for practical motor acceleration curves. Use of speed-distance curve for finding cutting off point. Use of slide rule for motor characteristic curves in speed-time curve calculations and determination of the capacity of railway motors. Castiglioni method compared with Mailloux method of speed-time calculations.

4. INSULATION AND DIELECTRIC PHENOMENA

PROBLEMS OF HIGH-TENSION TRANSMISSION LINES

Report of Sub-Committee on Transmission

Introduction by P. W. Sothman, Chairman **Vol. xxxiii—1914, pp. 105-118**

Outline of leading problems in building and operating high-tension lines. Selection of materials and equipment. Factors that enter into the design of the line structure. Extracts from reports of experience from various companies operating high-tension lines, with special reference to insulation.

APPENDIX I, pages 119-122. Deterioration of Porcelain Insulators in Service, by J. A. Brundige. Causes of molecular fatigue and methods of detection.

APPENDIX II, pages 123-124. Radius of Influence of a Direct Lightning Stroke, by L. C. Nicholson.

APPENDIX III, pages 124-127. Transmission Line Problems in the West, by P. M. Downing. Brief notes on experience in operation.

APPENDIX IV, pages 127-129. Switching, by G. Faccioli. Effect of switching in producing oscillations.

PRACTICAL OPERATION OF SUSPENSION INSULATORS

H. W. Buck **Vol. xxxiii—1914, pp. 131-137**

Brief review of difficulties experienced in operation of suspension insulators on transmission lines. Wind pressure and sleet loads. Calculation and design of lines to meet stresses.

Discussion (including that of paper by P. W. Sothman), pages 138-154, by Messrs. H. W. Buck, F. W. Peek, Jr., Charles E. Waddell, Percy H. Thomas, R. J. McClelland, V. Karapetoff, P. M. Lincoln, Farley Osgood, J. A. Sandford, Jr., E. R. Albrecht, William L. Puffer, Ernest V. Pannell, Julian C. Smith, E. A. Lof, C. O. Mailloux, E. M. Hewlett, H. W. Buck and K. C. Randall.

General remarks on transmission line construction and operation. Insulation theory and insulator troubles. Tower specifications. Choice of conductor and method of stringing. Deterioration of porcelain. Insulator design.

THEORY OF THE CORONA

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Influence of electric field upon the molecules in decreasing the energy required for ionization. Manner in which Peek's law of visual corona was derived.

INFLUENCE OF TRANSFORMER CONNECTIONS ON OPERATION

Louis F. Blume **Vol. xxxiii—1914, pp. 735-752**

Discussion of relative advantages and disadvantages in operation of the more important three-phase transformer connections. Three conditions of operation are given: First, normal; second, operation of a bank with one phase disabled; third, effect of line grounds on operation. Analysis of insulation stresses at relatively low frequencies to which transformers are subject in either normal or abnormal conditions of operation. These frequencies include the fundamental or generated frequency and its harmonics and the natural frequency of the system. The behavior of three-phase auto-transformers under the various conditions of operation is also analyzed.

Discussion, incorporated with that of paper by J. P. Jollyman, P. M. Downing and F. G. Baum on "Experience of the Pacific Gas and Electric Co. with the Grounded Neutral."

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General discussion of methods and precautions in measuring extremely high e.m.fs. Description of experiments with conductor near absolute zero of temperature, showing electrical resistance to be practically zero.

PROVISIONAL SPECIFICATION FOR INSULATOR TESTING

Covering Inspection and Tests of High-Tension Line Insulators of Porcelain, for over 25,000 Volts

Vol. xxxiii—1914, pp. 1107-1119

Discussion, pages 1120-1132, by Messrs. Percy H. Thomas, E. E. F. Creighton, Edward Bennett, E. M. Hewlett, Farley Osgood, S. C. Lindsay, John B. Fisken, F. W. Peek, Jr., and William B. Jackson.

General remarks on scope and character of the specifications.

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Analysis of e.m.f. stresses in insulation. Tests that must be made, followed by description of new type of oscillating voltmeter for measuring peak values.

Discussion, pages 1207-1215, by Messrs. W. A. Del Mar, C. O. Mailloux, Henry G. Scott, E. E. F. Creighton, Charles L. Fortescue, Percy H. Thomas, J. R. Craighead, W. I. Middleton and Chester L. Dawes.

General remarks on voltage testing of cables—what voltage, what sources. Cause of third-harmonic disturbances and effect of peak e.m.f.

ECONOMY IN THE OPERATION OF 55,000-VOLT INSULATORS

M. T. Crawford **Vol. xxxiii—1914, pp. 1429-1434**

Brief outline of the operating experiences on three 55,000-volt lines, two of which have been in service 10 years and one 5 years, covering the progress of insulator construction. A device is described by means of which defective insulators can be readily detected in the very early stages of deterioration.

Discussion, pages 1435-1440, by Messrs. J. Harisberger, M. H. Gerry, Jr., V. H. Greisser, A. A. Miller, H. R. Noack, T. R. Cornick, P. M. Lincoln, L. T. Merwin, L. J. Corbett, Ralph W. Pope and E. Woodbury.

Experience in the operation of high-tension insulators.

THE CORONA PRODUCED BY CONTINUOUS POTENTIALS

Stanley P. Farwell **Vol. xxxiii—1914, pp. 1631-1666**

Experimental investigation of the corona around small wires as produced by continuous potentials up to 15,000 volts, obtained from a series of 500-volt generators.

The wire and coaxial cylinder method was employed for a number of experiments. Critical voltages and characteristic potential difference and current curves for different sized wires. The effect of pressure upon appearance of corona, critical voltage, and current. Characteristic curves of the effect of varying pressure, moisture and temperature.

Discussion, pages 1667-1671, by Messrs. L. W. Chubb, A. E. Kennelly, P. M. Lincoln, Max von Recklinghausen, L. T. Robinson, Selby Haar, F. W. Peek, Jr., A. E. Kennelly, and S. P. Farwell.

Comparison of a-c. with d-c. corona losses.

EFFECT OF ALTITUDE ON THE SPARK-OVER VOLTAGES OF BUSHINGS, LEADS AND INSULATORS

F. W. Peek, Jr. **Vol. xxxiii—1914, pp. 1721-1730**

Investigation of the effect of altitude and temperature on the surface spark-over of leads and insulators. Correction factors for various standard types. Data tabulated and plotted.

Discussion incorporated with that of paper by A. O. Austin on "Insulator Depreciation and Effect on Operation."

INSULATOR DEPRECIATION AND EFFECT ON OPERATION

A. O. Austin **Vol. xxxiii—1914, pp. 1731-1734**

Analytical discussion of mechanical defects in line insulators as developed by actual practice. Presentation of method of calculating the probable depreciation of insulators.

Discussion (including that of paper by F. W. Peek, Jr.), pages 1745-1766, by Messrs. Harvey L. Curtis, D. B. Rushmore, E. D. Eby, P. W. Sothman, Selby Haar, Charles P. Steinmetz, E. E. F. Creighton, Farley Osgood, F. W. Peek, Jr., Edward J. Cheney, H. H. Sticht, H. H. Schneider and R. P. Jackson.

Investigation of surface resistance of various materials with quantitative results plotted as curves. General remarks on line insulators and tests for location of faulty ones.

SPECIFICATION AND ANALYTICAL PROCEDURE FOR 30 PER CENT HEVEA RUBBER INSULATING COMPOUND

Report of the Joint Rubber Insulation Committee Appointed by a Group of Manufacturers and Users of Rubber Compounds, 1911-1914

Vol. xxxiii—1914, pp. 1767-1786

Part I—General Report.
Part II—Analytical Procedure
Part III—Explanation of Procedure.
Part IV—Specification.
Part V—Explanation of Specification.

5. ELECTRIC CONDUCTORS

PRACTICAL OPERATION OF SUSPENSION INSULATORS

H. W. Buck **Vol. xxxiii—1914, pp. 131-137**

Brief review of difficulties experienced in operation of suspension-insulators on transmission lines. Wind pressure and sleet loads. Calculation and design of lines to meet stresses.

Discussion (including that of paper by P. W. Sothman), pages 138-154, by Messrs. H. W. Buck, F. W. Peek, Jr., Charles E. Waddell, Percy H. Thomas, R. J. McClelland, V. Karapetoff, P. M. Lincoln, Farley Osgood, J. A. Sandford, Jr., E. R. Albrecht, William L. Puffer, Ernest V. Pannell, Julian C. Smith, E. A. Lof, C. O. Mailloux, E. M. Hewlett, H. W. Buck and K. C. Randall.

General remarks on transmission line construction and operation. Insulation theory and insulator troubles. Tower specifications. Choice of conductor and method of stringing. Deterioration of porcelain. Insulator design.

DISTRIBUTION OF ELECTRICAL ENERGY

Report of Sub-Committee on Distribution

P. Junkersfeld, Chairman **Vol. xxxiii—1914, pp. 211-217**

General remarks on desirability of few large substations compared with many small ones. Bibliography of distribution for light, power and railways. Cables and underground construction.

APPENDIX I, pages 217-222. Three-Wire D.C. Distribution, by Philip Torchio. Brief review of practice.

APPENDIX II, pages 222-235. Alternating-Current Distribution, by H. B. Gear. Brief outline of practice for distribution of electric energy in bulk and also for general use. Typical circuits and networks. Demand factors. Advice for selection of apparatus for substations and distribution systems.

APPENDIX III, pages 236-240. Effect of Consumers' Apparatus and Wiring on Distribution, by H. Goodwin. Rules for governing consumers' load characteristics.

APPENDIX IV, pages 240-251. Direct-Current Distribution for Surface Railways—Urban Service, by R. H. Rice. General analytical discussion of the system including substations, feeders, working conductors and return.

APPENDIX V, pages 251-259. Direct-Current Distribution for Underground and Elevated Railways, by E. J. Blair. Working or contact conductor layout for different types of systems in actual use with special regard to feeding points and sectionalization.

APPENDIX VI, pages 259-261. Direct-Current Distribution for Interurban and Steam Railroads, by W. G. Carlton. Brief notes on various types and word about choice of working e.m.f.

APPENDIX VII, pages 261-262. A-C. Distribution for Interurban and Steam Railroads, by W. S. Murray. Recommendation of single-phase overhead construction.

APPENDIX VIII, pages 262-266. The Relation of Distribution Problems and Switching Apparatus, by E. B. Merriam. Brief discussion of factors most affected by switching, such as reliability of service, protection of system from disturbances, and safety of operators.

APPENDIX IX, pages 266-269. Distribution for Street Lighting Service, by Paul M. Lincoln. Advantages of constant-current series system of distribution.

Discussion, pages 270-282, by Messrs. H. L. Wallau, Philip Torchio, S. D. Sprong, D. W. Roper, E. M. Hewlett, H. R. Summerhayes, John B. Taylor, E. W. Trafford, J. T. Kelly, Jr., John Murphy, H. B. Gear and Carl Schwartz.

General remarks on operation of distribution circuits and experience with control, protective and switching apparatus of various types.

ENGINEERING DATA RELATING TO HIGH-TENSION TRANSMISSION SYSTEMS

Sub-Committee Report Prepared by the Chairman.

Vol. xxxiii—1914, pp. 1013-1089

Introduction. Classified list of power companies reporting and brief outline of scope of each report. Typical classification of information received by the committee. Drawings and tables for transmission line construction.

Discussion, pages 1090-1105, by Messrs. John B. Fisken, Percy H. Thomas, S. C. Lindsay, Ernest V. Pannell, E. E. F. Creighton, F. W. Peek, Jr., R. Fleming, H. H. Norton, M. von Recklinghausen, D. D. Ewing, R. E. Argersinger, E. A. Lof and Selby Haar.

Explanation of cause of deterioration of high-tension conductors. Operation of reverse power relays. European high-tension practice. Comprehensive list of references to high-tension engineering articles in periodicals of the world.

VOLTAGE TESTING OF CABLES

W. I. Middleton and Chester L. Dawes **Vol. xxxiii—1914, pp. 1185-1206**

Analysis of e.m.f. stresses in insulation. Tests that must be made, followed by description of new type of oscillating voltmeter for measuring peak values.

Discussion, pages 1207-1215, by Messrs. W. A. Del Mar, C. O. Mailloux, Henry G. Stott, E. E. F. Creighton, Charles L. Fortescue, Percy H. Thomas, J. R. Craighead, W. I. Middleton and Chester L. Dawes.

General remarks on voltage testing of cables—what voltage, what sources. Cause of third-harmonic disturbances and effect of peak, e.m.f.

A DISTRIBUTION SYSTEM FOR POWER PURPOSES

F. D. Nims **Vol. xxxiii—1914, pp. 1299-1304**

Description of the distribution system of the Western Canada Power Company, Limited, touching on the overhead and underground systems in general. Advantages obtained by duplicating lines, both for eliminating outages and from a financial standpoint. Also the advantages obtained by using a steel-taped lead-armored cable placed directly in the ground, figures showing the exact cost of such an installation being given.

Discussion, pages 1305-1313, by Messrs. J. B. Fisken, P. M. Lincoln, F. L. Rohrbach, C. S. MacCalla, H. V. Carpenter, Edward Woodbury, G. B. Rosenblatt, John Harisberger, L. J. Corbett, Paul Lebenbaum, M. T. Crawford and F. D. Nims.

Experience with underground cables without ducts.

6. MAGNETIC PROPERTIES AND TESTING OF IRON

MAGNETIC AND OTHER PROPERTIES OF ELECTROLYTIC IRON MELTED IN VACUO

Trygve D. Yensen **Vol. xxxiii—1914, pp. 451-475**

Brief mention of early work done in the study of magnetic properties of iron and iron alloys. Description of the construction of vacuum furnace for melting iron and permeameter for testing short bars. Account of methods of preparing specimens and testing their magnetic properties. Effect of heat treatment on magnetic properties shown by curves and tables. Discussion of equilibrium diagram of iron-carbon alloys with special reference to magnetic properties.

No discussion.

7. BATTERIES

SELF-CONTAINED PORTABLE ELECTRIC MINE LAMPS

H. O. Swoboda **Vol. xxxiii—1914, pp. 385-396**

General requirements of safety lamp for mines. Description of construction of groups of prize-winning electric lead storage battery safety lamps. Method of caring for lamps and batteries. Cost of operation.

Discussion, pages 397-401, by Messrs. H. H. Clark, H. H. Smith, R. C. Burrows, and H. O. Swoboda.

Advantages of the alkaline battery.

8. TRANSFORMERS

OUTDOOR SUBSTATIONS IN NEW ENGLAND

Fred L. Hunt **Vol. xxxiii—1914, pp. 65-89**

Brief description and discussion of two substations of the Amherst Power Company, giving the basis of choice between the outdoor and indoor stations. Care of transformers and oil switchers in freezing weather.

Discussion incorporated with that of paper by Leslie L. Perry on "Outdoor Substations in the Middle West."

A MILLIAMPERE CURRENT TRANSFORMER

Edward Bennett **Vol. xxxiii—1914, pp. 571-586**

The drawing and specification for a transformer for use with oscillograph for measuring current of a single insulator or a few feet of high-tension transmission line.

The transformer relations are discussed; the methods of determining the transformer constants are outlined and the performance of transformers constructed in accordance with the specifications is determined.

A series of oscillograms is given to illustrate some of the applications of the transformer, such as to the study of corona, high-tension insulators, and leakage currents in evacuated lamps.

Discussion, pages 586-588, by Messrs. J. B. Whitehead, J. R. Craighead and Edward Bennett.

Criticisms of paper.

EXPERIENCE WITH LINE TRANSFORMERS

D. W. Roper **Vol. xxxiii—1914, pp. 685-697**

Analysis of the transformer troubles for one year on a system having nearly 15,000 transformers installed. Curves showing the record of burnouts of four different makes of transformers are used as a basis for a discussion of effect of the value placed on continuous service in the selection of transformer. The results of experiment with improved lightning protection are given, showing how the troubles were reduced.

Discussion, pages 698-710, by Messrs. W. S. Moody, A. D. Fishel, H. W. Hough, Paul M. Lincoln, Joseph Franz, M. O. Troy, E. E. F. Creighton H. B. Alverson, W. L. Granger, W. J. Wooldridge and D. W. Roper.

General remarks on design, operation and protection of transformer installations.

INHERENT VOLTAGE RELATIONS IN Y AND DELTA CONNECTIONS

Royal W. Sorenson and Walter L. Newton **Vol. xxxiii—1914, pp. 711-727**

Results of experiments made with a miniature simple transmission system to demonstrate the inherent voltage relations with different combinations of Y and delta connections, all inductive and capacity effects in the transmission line being eliminated. The tests were made under constant conditions, with non-inductive load.

The authors give the results of four groups of tests, on four different systems of connections, pointing out the advantages and disadvantages of the several systems. In each case tests were made without load, with balanced load, and with load on one phase only, for various conditions of grounding. Typical voltage diagrams are given, to show what happens under various conditions of load.

Certain cases where the use of auto-transformers is advantageous, and the effects of different ways of connecting them, are discussed.

Discussion, pages 728-733, by Messrs. Waldo V. Lyon, A. E. Kennelly and Harold Pender, F. W. Peek, Jr., Louis F. Blume, F. C. Green, C. L. Fortescue, P. M. Lincoln, J. M. Weed and D. C. Jackson.

General remarks on the third harmonic in transformer operation.

INFLUENCE OF TRANSFORMER CONNECTIONS ON OPERATION

Louis F. Blume **Vol. xxxiii—1914, pp. 735-752**

Discussion of relative advantages and disadvantages in operation of the more important three-phase transformer connections. Three con-

ditions of operation are given: First, normal; second, operation of a bank with one phase disabled; third, effect of line grounds on operation. Analysis of insulation stresses at relatively low frequencies to which transformers are subject in either normal or abnormal conditions of operation. These frequencies include the fundamental or generated frequency and its harmonics and the natural frequency of the system. The behavior of three-phase auto-transformers under the various conditions of operation is also analyzed.

Discussion incorporated with that of paper by J. P. Jollyman, P. M. Downing and F. G. Baum on "Experience of the Pacific Gas and Electric Co. with the Grounded Neutral."

A STUDY OF SOME THREE-PHASE SYSTEMS

Charles Fortescue **Vol. xxxiii—1914, pp. 753-756**

Discussion of the star-star, delta-delta, delta-star and star-delta connections in order and their individual peculiarities and characteristics, precautions that must be taken in operation to avoid trouble, and where and when the system may be grounded with best results.

Discussion incorporated with that of paper by J. P. Jollyman, P. M. Downing and F. G. Baum on "Experience of the Pacific Gas and Electric Co. with the Grounded Neutral."

EXPERIENCE OF PACIFIC GAS AND ELECTRIC CO. WITH THE GROUNDED NEUTRAL

J. P. Jollyman, P. M. Downing and F. G. Baum **Vol. xxxiii—1914, pp. 757-772**

Outline of the distributing system of the Pacific Gas and Electric Company of California which operates at 60 kv., the transformers being Y-connected, with the neutrals solidly grounded.

Discussion (including that of papers by Louis F. Blume and Charles Fortescue), pages 773-802, by Messrs. Guido Semenza, F. F. Brand, W. W. Lewis, V. M. Montsinger, C. M. Davis, L. F. Blume, H. S. Osborne, F. E. Haskell, H. S. Osborne, C. O. Mailloux, E. E. F. Creighton, John B. Taylor, F. C. Green, P. M. Lincoln, D. W. Roper, F. W. Peek, Jr., J. R. Werth, C. L. Fortescue and Max H. Collbohm.

Summary of transformer connection practice in Italy. Classification of high tension transmission systems of the world on basis of star and delta. Operating results of six great transmission systems. Results of tests on effect of capacity and inductance upon third harmonics in star auto-transformers. Comparison of star and delta from point of view of telephone disturbances. The problem of insulating transmission lines.

THE EFFECT OF DELTA AND STAR CONNECTIONS UPON TRANSFORMER WAVE FORMS

Leslie F. Curtis **Vol. xxxiii—1914, pp. 1273-1277**

Tests with the oscillograph to show the distortions in the no-load exciting current and voltage waves of three single-phase step-up transformers when the windings of the generator and both sides of the transformers were connected in all possible symmetrical delta and star relations.

Oscillograms are given in each case and the relations between the flux, voltage, exciting current, and the hysteresis cycle are shown in two instances.

Discussion, pages 1278-1282, by Messrs. P. M. Lincoln, L. J. Corbett, A. A. Miller, E. G. Robinson, Jr., M. H. Gerry, Jr., L. T. Merwin, Livingston P. Ferris, H. V. Carpenter and L. F. Curtis.

General remarks on transformer construction.

9. ELECTRICAL MACHINERY AND APPARATUS

SIXTY-CYCLE SYNCHRONOUS CONVERTERS

L. P. Crecelius **Vol. xxxiii—1914, pp. 353-365**

Notes on choice of synchronous converter for sixty-cycle operation. Extracts from purchasers' contract and specifications.

No discussion.

THE DEVELOPMENT OF THE ELECTRIC MINE LOCOMOTIVE

G. M. Eaton **Vol. xxxiii—1914, pp. 403-414**

Evolution of coal mine locomotive with illustrations. Various types of mine locomotives, construction shown and briefly discussed. Also brief reference to various types of motors with different methods of lubrication and bearing construction. Design data plotted to show tendency of future development.

Discussion, pages 415-429, by Messrs. W. W. Miller, C. W. Beers, Carl J. E. Waxbom, Graham Bright, F. L. Stone, G. M. Eaton, L. J. Ilsley, W. A. Thomas, G. H. Shapter, E. H. Martindale and N. W. Storer.

General remarks on constructional features of mine locomotives. Data on costs, repairs and troubles from actual experience. Experience with ball bearings.

MINE SUBSTATIONS
Motor-Generator Sets vs. Synchronous Converters

Will H. Hoen **Vol. xxxiii—1914, pp. 431-437**

Comparison of synchronous converters, synchronous motor-generators and induction motor generators as to starting characteristics, efficiency and performance on mine loads.

Discussion incorporated with that of paper by H. Booker on "Mine Substations—Their Construction and Operation."

MINE SUBSTATIONS
Their Construction and Operation

H. Booker **Vol. xxxiii—1914, pp. 439-444**

Brief practical discussion of layout, operation and maintenance of substations around coal mines. List of common defects in design of substations and faults in the organization of the operating force.

Discussion (including that of paper by Will M. Hoen), pages 445-449, by Messrs. W. A. Thomas, P. M. Lincoln, N. Stahl and Will M. Hoen.

Use of synchronous converters in mines. Load characteristics of mines.

SOLENOIDS

Charles R. Underhill **Vol. xxxiii—1914, pp. 477-509**

Fundamental equation for design of solenoids and plunger magnets. Tables and curves giving constants for use in formulas. Characteristic curves of actual solenoids and plunger magnets.

Discussion, pages 510-517, by Messrs. Charles W. Burrows, E. R. Carichoff, and C. R. Underhill.

Equations for magnetic field of solenoids.

THE FUTURE OF ELECTRIC HEATING AND COOKING IN MARINE SERVICE
H. J. Mauger **Vol. xxxiii—1914, pp. 659-668**

General remarks on use and future of electric cooking on board ship. Brief description of equipment of Battleship Texas and results of tests of power consumption. Advantages of electric cooking and heating.

Discussion, pages 669-672, by Messrs. W. S. Hadaway, E. F. Dutton, H. J. Mauger and Frank T. Leilich.

Disadvantages of electric cooking on board ship. Difficulties of building resistors for high surface temperatures.

RELATIVE MERITS OF Y AND DELTA CONNECTION FOR ALTERNATORS
T. S. Eden **Vol. xxxiii—1914, pp. 803-806**

Brief statement of advantages and disadvantages of each system.

Discussion incorporated with that of paper by Cassius M. Davis on "Delta and Y Connections for Railway Transmission and Distribution."

ELECTRIC HEATING AS APPLIED TO MARINE SERVICE
C. S. McDowell and D. M. Mahood **Vol. xxxiii—1914, pp. 839-850**

A comparison of convector and radiant heaters, the proper use of each type being shown, for space heating on shipboard with metal decks and bulkheads.

Curves showing results obtained on tests to determine the best type of heater for shipboard and desirable features of heater are indicated.

Discussion, pages 851-855, by Messrs. W. S. Hadaway, Jr., Alfred E. Waller, Charles D. Knight, D. B. Rushmore, F. C. Caldwell, D. M. Mahood and H. A. Hornor.

Results of electric heating tests at the University of Nebraska. Relative merits of open-coil and enclosed heater units.

THE ELECTRICALLY DRIVEN GYROSCOPE IN MARINE WORK
H. C. Ford **Vol. xxxiii—1914, pp. 857-871**

Definition of gyroscope and brief statement of practical uses to which it has been put:

A general description of the gyro-compass as adopted by the United States Navy for use on all the battleships and submarine vessels, and of the many electrical and mechanical devices that have been developed by E. A. Sperry to perform the various functions whereby an instrument of great precision has been secured.

Brief mention of large gyroscopes which are capable of counteracting enormous wave forces and completely stabilizing any ship against rolling in the heaviest seas.

Discussion, page 872, by Messrs. Alfred E. Waller and H. C. Ford. Remarks on stabilizing action of gyroscope.

DIRECT-CURRENT MOTORS FOR COAL AND ORE BRIDGES
R. H. McLain **Vol. xxxiii—1914, pp. 873-884**

Brief description of the mechanical arrangement of a coal bridge. Performance characteristic curves and discussion of type of motors suited to the work and the proper methods of gearing the motor for most economical results.

Discussion, pages 885-886, by Messrs. D. B. Rushmore, S. C. Lindsay, T. E. Tynes and R. H. McLain.

CONCATENATED INDUCTION MOTORS FOR ROLLING MILL DRIVE
William O. Oschmann **Vol. xxxiii—1914, pp. 899-920**

Description of a six-speed concatenated induction motor set for driving the finishing rolls of a 12-stand continuous mill and analysis of the conditions that determined choice of prime mover and motor drive control. Load diagram and power characteristics curves.

Discussion, page 921, by Messrs. Rudolph Tschentscher, T. E. Tynes and A. E. Averrett.

APPLICATION OF ELECTRIC MOTORS TO GOLD DREDGES
Girard B. Rosenblatt **Vol. xxxiii—1914, pp. 1405-1416**

Classification of gold dredges and outline of requirements for electric operation. Choice of motor and specifications for design of digging motor.

Discussion, pages 1417-1427, by Messrs. Ford W. Harris, M. H. Gerry, Jr., F. A. Ross, L. K. Armstrong, W. M. Sheppard, A. A. Miller and C. B. Rosenblatt.

Experience with electric dredges.

USE OF REACTANCE WITH SYNCHRONOUS CONVERTERS
An Insurance to Continuity of Service and a Protection to Apparatus
J. L. McK. Yardley **Vol. xxxiii—1914, pp. 1521-1533**

Results of overload and short-circuit tests upon two synchronous converters of widely different operating characteristics in circuit with auxiliary reactors. In the one case the reactor is in the a-c. circuit and in the other in the d-c. circuit.

Division of synchronous converter installations into a few general classes with respect to the character and exactions of the service conditions under which they are required to operate with respect to the need or desirability of employing protective reactance, and also with respect to the general design or type of the reactor to be employed.

Discussion, pages 1534-1547, by Messrs. D. B. Rushmore, Philip Torchio, H. W. Buck, H. R. Summerhayes, J. J. Frank, N. W. Storer, George T. Hanchett, Carl J. Fechheimer, Mr. Woodward, Mr. Howard, Mr. Burnham, J. L. McK. Yardley and John B. Taylor.

General remarks on design and application of protective reactors.

10. PRIME MOVERS AND STEAM BOILERS

CONCATENATED INDUCTION MOTORS FOR ROLLING MILL DRIVE
William O. Oschmann **Vol. xxxiii—1914, pp. 899-920**

Description of a six-speed concatenated induction motor set for driving the finishing rolls of a 12-stand continuous mill and analysis of the conditions that determined choice of prime mover and motor drive control. Load diagrams and power characteristic curves.

Discussion, page 921, by Messrs. Rudolph Tschentscher, T. E. Tynes and A. E. Averrett.

PRESENT STATUS OF PRIME MOVERS
H. G. Stott, R. J. S. Pigott and W. S. Gorsuch **Vol. xxxiii—1914, pp. 1133-1166**

Concise presentation of the present status of heat engines and hydraulic turbines in commercial use for the conversion of the energy of fuel and water into mechanical energy for the production of electric energy.

The various types are compared as to relative importance, capacity,

efficiency, weight, cost and economy, which are illustrated by curves plotted on kilowatt basis.

Curves are plotted showing the investment and fuel costs of the different heat engine units, on the basis of percentage of normal full load rating of machines.

Discussion, pages 1167-1183, by Messrs. R. Tschentscher, J. R. Bibbins, H. M. Hobart, E. D. Dreyfus, H. G. Stott, S. Barfoed, Franklin M. Farwell, W. S. Gorsuch and R. J. S. Pigott.

General remarks and data on the cost of electric energy production with different prime movers under various conditions.

11. POWER PLANTS

PROTECTIVE REACTANCE IN LARGE POWER STATIONS

James Lyman, Allen M. Rossman and Leslie L. Perry **Vol. xxxiii—1914, pp. 22-45**

General discussion of the various uses of reactance to limit the flow of energy under abnormal conditions. Typical busbar arrangements. Diagrams giving relation between maximum current and reactance used in various ways. Diagrams of relation between maximum current and number of generators running. Equation for maximum current.

Discussion, pages 46-55, by Messrs. Philip Torchio, W. S. Moody, Henry G. Stott, Paul M. Lincoln, V. Karapetoff, Harry R. Woodrow, Cassius M. Davis, Allen M. Rossman, O. J. Ferguson and Alex. E. Bauhan.

Discussion of the use and design of reactance coils. Equation for instantaneous current.

THE ECONOMICAL CAPACITY OF A COMBINED HYDROELECTRIC AND STEAM POWER PLANT

Cary T. Hutchinson **Vol. xxxiii—1914, pp. 155-192**

Development of method of determining the point of economical capacity of a hydroelectric plant on a variable-flow stream with and without pondage and with steam auxiliary. Choice of basic stream flow. Complete data on Susquehanna River as practical example. Determination of capacity of steam auxiliary. Per cent deficiency and per cent load charts for use in calculations. Cost of hydroelectric plants and energy production. Numerical examples of the use of the method.

Discussion incorporated with that of paper by H. M. Hobart on "The Cost of Electricity at the Source."

THE COST OF ELECTRICITY AT THE SOURCE

H. M. Hobart **Vol. xxxiii—1914, pp. 192-200**

The Stott-Gorsuch method is applied to the determination of the cost of manufacturing electricity in a 60-cycle station of 100,000 kilowatts installed capacity. A method is indicated for tracing through the increase in the cost of the electricity at later stages of its journey from the source to the consumer.

Discussion (including that of paper by Cary T. Hutchinson) pages 201-210, by Messrs. J. W. Lieb, Jr., H. R. Summerhayes, H. W. Buck, Frederick A. Scheffler, H. L. Wallau, H. B. Alverson, O. K. Harlan, H. C. Abell, A. H. Kruesi, V. Karapetoff, Frederick G. Strong, G. L. Knight and H. M. Hobart.

General remarks on cost of equipping electric generating stations and some actual cost data.

METHODS OF KEEPING DOWN PEAKS ON POWER PURCHASED ON A PEAK BASIS

T. E. Tynes **Vol. xxxiii—1914, pp. 887-892**

Brief statement of two general ways of reducing peaks followed by description of a special peak-taking device.

Discussion, pages 893-898, by Messrs. Rudolph Tschentscher, Paul M. Lincoln, J. Lester Woodbridge, J. R. Bibbins, R. H. McLain, E. D. Dreyfus and T. E. Tynes.

General remarks on automatic peak absorption. Discussion of the economic expediency of absorbing peaks as against straight purchase of energy.

ELECTRICAL FEATURES OF THE U. S. RECLAMATION SERVICE

F. H. Newell **Vol. xxxiii—1914, pp. 1609-1624**

Brief outline of electrical development problems of the Reclamation Service, followed by short descriptions of the chief developments. Tabulated data on the electrical installations and power plants of the Reclamation Service.

Discussion, pages 1625-1629, by Messrs. Paul Spencer, Ralph W. Pope, J. E. Kershner, P. M. Lincoln, H. A. Hornor, Vladimir Karapetoff, Carl Hering, Mr. Bender, H. Goodwin, Jr., and F. H. Newell.

General remarks on the cost of energy for hydroelectric developments.

13. TRANSMISSION

PROBLEMS OF HIGH-TENSION TRANSMISSION LINES
Report of Sub-Committee on Transmission

Introduction by P. W. Sothman, Chairman **Vol. xxxiii—1914, pp. 105-118**

Outline of leading problems in building and operating high-tension lines. Selection of materials and equipment. Factors that enter into the design of the line structure. Extracts from reports of experience from various companies operating high-tension lines with special reference to insulation.

APPENDIX I, pages 119-122. Deterioration of Porcelain Insulators in Service, by J. A. Brundige. Causes of molecular fatigue and methods of detection.

APPENDIX II, pages 123-124. Radius of Influence of a Direct Lightning Stroke, by L. C. Nicholson.

APPENDIX III, pages 124-127. Transmission Line Problems in the West, by P. M. Downing. Brief notes on experience in operation.

APPENDIX IV, pages 127-129. Switching, by G. Faccioli. Effect of switching in producing oscillations.

PRACTICAL OPERATION OF SUSPENSION INSULATORS

H. W. Buck **Vol. xxxiii—1914, pp. 131-137**

Brief review of difficulties experienced in operation of suspension insulators on transmission lines. Wind pressure and sleet loads. Calculation and design of lines to meet stresses.

Discussion (including that of paper by P. W. Sothman), pages 138-154, by Messrs. H. W. Buck, F. W. Peek, Jr., Charles E. Waddell, Percy H. Thomas, R. J. McClelland, V. Karapetoff, P. M. Lincoln, Farley Osgood, J. A. Sandford, Jr., E. R. Albrecht, William L. Puffer, Ernest V.

Pannell, Julian C. Smith, E. A. Lof, C. O. Mailloux, E. M. Hewlett, H. W. Buck and K. C. Randall.

General remarks on transmission line construction and operation. Insulation theory and insulator troubles. Tower specifications. Choice of conductor and method of stringing. Deterioration of porcelain. Insulator design.

SOME SIMPLE EXAMPLES OF TRANSMISSION LINE SURGES

W. S. Franklin **Vol. xxxiii—1914, pp. 545-559**

Analytical discussion of waves produced in transmission lines by surging. The ribbon wave and practical examples of its application.

Discussion, pages 560-569, by Messrs. J. Murray Weed, A. G. Webster and A. Hamilton-Ellis.

Mathematical analysis of transmission line performance under surging conditions.

EXPERIENCES WITH LINE TRANSFORMERS

D. W. Roper **Vol. xxxiii—1914, pp. 685-679**

Analysis of the transformer troubles for one year on a system having nearly 15,000 transformers installed. Curves showing the record of burnouts of four different makes of transformers are used as a basis for a discussion of effect of the value placed on continuous service in the selection of transformers. The results of experiment with improved lightning protection are given, showing how the troubles were reduced.

Discussion, pages 698-710, by Messrs. W. S. Moody, A. D. Fishel, H. W. Hough, Paul M. Lincoln, Joseph Franz, M. O. Troy, E. E. F. Creighton, H. B. Alverson, W. L. Granger, W. J. Wooldridge, and D. W. Roper.

General remarks on design, operation and protection of transformer installations.

INHERENT VOLTAGE RELATIONS IN Y AND DELTA CONNECTIONS

Royal W. Sorenson and Walter L. Newton **Vol. xxxiii—1914, pp. 711-727**

Results of experiments made with a miniature simple transmission system to demonstrate the inherent voltage relations with different combinations of Y and delta connections, all inductive and capacity effects in the transmission line being eliminated. The tests were made under constant conditions, with non-inductive load.

The authors give the results of four groups of tests, on four different systems of connections, pointing out the advantages and disadvantages of the several systems. In each case tests were made without load, with balanced load, and with load on one phase only, for various conditions of grounding. Typical voltage diagrams are given, to show what happens under various conditions of load.

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Discussion, pages 728-733, by Messrs. Waldo V. Lyon, A. E. Kennelly and Harold Pender, F. W. Peek, Jr., Louis F. Blume, F. C. Green, C. L. Fortescue, P. M. Lincoln, J. M. Weed and D. C. Jackson.

General remarks on the third harmonic in transformer operation.

INFLUENCE OF TRANSFORMER CONNECTIONS ON OPERATION

Louis F. Blume **Vol. xxxiii—1914, pp. 735-752**

Discussion of relative advantages and disadvantages in operation of the more important three-phase transformer connections. Three conditions

of operation are given: First, normal; second, operation of a bank with one phase disabled; third, effect of line grounds on operation. Analysis of insulation stresses at relatively low frequencies to which transformers are subject in either normal or abnormal conditions of operation. These frequencies include the fundamental or generated frequency and its harmonics and the natural frequency of the system. The behavior of three-phase auto-transformers under the various conditions of operation is also analyzed.

Discussion, incorporated with that of paper by J. P. Jollyman, P. M. Downing and F. G. Baum on "Experience of the Pacific Gas and Electric Co. with the Grounded Neutral."

A STUDY OF SOME THREE-PHASE SYSTEMS

Charles Fortescue **Vol. xxxiii—1914, pp. 783-756**

Discussion of the star-star, delta-delta, delta-star and star-delta connections in order and their individual peculiarities and characteristics, precaution that must be taken in operation to avoid trouble, and where and when the system may be grounded with best results.

Discussion incorporated with that of paper by J. P. Jollyman, P. M. Downing and F. G. Baum on "Experience of the Pacific Gas and Electric Co. with the Grounded Neutral."

EXPERIENCE OF PACIFIC GAS AND ELECTRIC CO. WITH THE GROUNDED NEUTRAL

J. P. Jollyman, P. M. Downing and F. G. Baum **Vol. xxxiii—1914, pp. 767-772**

Outline of the distributing system of the Pacific Gas and Electric Company of California which operates at 60 kv., the transformers being Y-connected, with the neutrals solidly grounded.

Discussion (including that of papers by Louis F. Blume and Charles Fortescue), pages 773-802, by Messrs. Guido Semenza, F. F. Brand, W.W. Lewis, V. M. Montsinger, C. M. Davis, L. F. Blume, H. S. Osborne, F. E. Haskell, H. S. Osborne, C. O. Mailloux, E. E. F. Creighton, John B. Taylor, F. C. Green, P. M. Lincoln, D. W. Roper, F. W. Peek, Jr., J. R. Werth, C. L. Fortescue and Max H. Collbohm.

Summary of transformer connection practice in Italy. Classification of high tension transmission systems of the world on basis of star and delta. Operating results of six great transmission systems. Results of tests on effect of capacity and inductance upon third harmonics in star auto-transformers. Comparison of star and delta from point of view of telephone disturbances. The problem of insulating transmission lines.

DELTA AND Y CONNECTIONS FOR RAILWAY TRANSMISSION AND DISTRIBUTION

Cassius M. Davis **Vol. xxxiii—1914, pp. 807-810**

Brief statement of problem of selecting connections for railway system.

Discussion, (including that of paper by T. S. Eden), pages 811-817, by Messrs. John B. Taylor, C. J. Fechheimer, E. G. Merrick, T. S. Eden, R. E. Doherty, Cassius M. Davis and Selby Haar.

Advantages of delta connection of alternators. Connection of turbo-alternators.

ENGINEERING DATA RELATING TO HIGH-TENSION TRANSMISSION SYSTEMS
Sub-Committee Report Prepared by the Chairman **Vol. xxxiii—1914, pp. 1013-1089**

Introduction. Classified list of power companies reporting and brief outline of scope of each report. Typical classification of information received by the committee. Drawings and tables for transmission line construction.

Discussion, pages 1090-1105, by Messrs. John B. Fisken, Percy H. Thomas, S. C. Lindsay, Ernest V. Pannell, E. E. F. Creighton, F. W. Peek, Jr., R. Fleming, H. H. Norton, M. von Recklinghausen, D. D. Ewing, R. E. Argersinger, E. A. Lof and Selby Haar.

Explanation of cause of deterioration of high-tension conductors. Operation of reverse power relays. European high-tension practice. Comprehensive list of references to high-tension engineering articles in periodicals of the world.

PROVISIONAL SPECIFICATION FOR INSULATOR TESTING
Covering Inspection and Tests of High-Tension Line Insulators of Porcelain, for over 25,000 Volts
Vol. xxxiii—1914, pp. 1107-1119

Discussion, pages 1120-1132, by Messrs. Percy H. Thomas, E. E. F. Creighton, Edward Bennett, E. M. Hewlett, Farley Osgood, S. C. Lindsay, John B. Fisken, F. W. Peek, Jr., and William B. Jackson.

General remarks on scope and character of the specifications.

150,000-VOLT TRANSMISSION SYSTEM
Some Operating Conditions of the Big Creek Development of the Pacific Light & Power Corporation
Edward Woodbury **Vol. xxxiii—1914, pp. 1283-1294**

Description of operating conditions on the 150,000-volt transmission 240-mile line of the Pacific Light and Power Corporation.

Appendixes describe the development of the system, and give comprehensive data relating to the equipment of the Big Creek transmission line.

Discussion, pages 1295-1298, by Messrs. J. Harisberger, J. B. Fisken, A. A. Miller, M. H. Gerry, Jr., E. Woodbury and V. H. Greisser.

Early experience with high-tension lines in the West. Necessity of synchronous condenser for very high-tension operation of long lines.

A DISTRIBUTION SYSTEM FOR POWER PURPOSES
F. D. Nims **Vol. xxxiii—1914, pp. 1299-1304**

Description of the distribution system of the Western Canada Power Company, Limited, touching on the overhead and underground systems in general. Advantages obtained by duplicating lines, both for eliminating outages and from a financial standpoint. Also the advantages obtained by using a steel-taped lead-armored cable placed directly in the ground, figures showing the exact cost of such an installation being given.

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Experience with underground cables without ducts.

ECONOMY IN THE OPERATION OF 55,000-VOLT INSULATORS

M. T. Crawford **Vol. xxxiii—1914, pp. 1429-1434**

Brief outline of the operating experience on three 55,000-volt lines, two of which have been in service 10 years and one 5 years, covering the progress of insulator construction. A device is described by means of which defective insulators can be readily detected in the very early stages of deterioration.

Discussion, pages 1435-1440, by Messrs. J. Harisberger, M. H. Gerry, Jr., V. H. Greisser, A. A. Miller, H. R. Noack, T. R. Cornick, P. M. Lincoln, L. T. Merwin, L. J. Corbett, Ralph W. Pope and E. Woodbury.

Experience in the operation of high-tension insulators.

REPORT BY THE JOINT COMMITTEE ON INDUCTIVE INTERFERENCE TO THE RAILROAD COMMISSION OF THE STATE OF CALIFORNIA

Vol. xxxiii—1914, pp. 1441-1485

Brief account of the formation of the Committee, its activities and results accomplished and recommendations for rulings by the Railroad Commission of the State of California, together with a scientific technical discussion in explanation of the results and recommendations.

Discussion, pages 1486-1508, by Messrs. P. N. Nunn, J. B. Fisken, A. H. Halloran, A. J. Bowie, Geo. S. Humphrey, J. C. Martin, L. J. Corbett, Chas. P. Kahler, L. T. Merwin, C. E. Rogers, A. J. Bowie, Jr., and A. H. Babcock.

Criticism and defense of the rules. Question of partisanship in the drafting of the rules.

EFFECT OF ALTITUDE ON THE SPARK-OVER VOLTAGES OF BUSHINGS, LEADS AND INSULATORS

F. W. Peek, Jr. **Vol. xxxiii—1914, pp. 1721-1730**

Investigation of the effect of altitude and temperature on the surface spark-over of leads and insulators. Correction factors for various standard types. Data tabulated and plotted.

Discussion incorporated with that of paper by A. O. Austin on "Insulator Depreciation and Effect on Operation."

INSULATOR DEPRECIATION AND EFFECT ON OPERATION

A. O. Austin **Vol. xxxiii—1914, pp. 1731-1734**

Analytical discussion of mechanical defects in line insulators as developed by actual practice. Presentation of method of calculating the probable depreciation of insulators.

Discussion (including that of paper by F. W. Peek, Jr.), pages 1745-1766, by Messrs. Harvey L. Curtis, D. B. Rushmore, E. D. Eby, P. W. Sothman, Selby Haar, Charles P. Steinmetz, E. E. F. Creighton, Farley Osgood, F. W. Peek, Jr., Edward J. Cheney, H. H. Sticht, H. H. Schneider and R. P. Jackson.

Investigation of surface resistance of various materials with quantitative results plotted as curves. General remarks on line insulators and tests for location of faulty ones.

SPECIFICATION AND ANALYTICAL PROCEDURE FOR 30 PER CENT HEVEA RUBBER INSULATING COMPOUND

Report of the Joint Rubber Insulation Committee Appointed by a Group of Manufacturers and Users of Rubber Compounds, 1911-1914

Vo. xxxiii—1914, pp. 1767-1786

Part I—General Report
Part II—Analytical Procedure
Part III—Explanation of Procedure
Part IV—Specification
Part V—Explanation of Specification

14. ELECTRIC SERVICE DISTURBANCES AND PROTECTION

PROBLEMS OF HIGH-TENSION TRANSMISSION LINES

Report of Sub-Committee on Transmission

Introduction by P. W. Sothman, Chairman **Vol. xxxiii—1914, pp. 105-118**

Outline of leading problems in building and operating high-tension lines. Selection of materials and equipment. Factors that enter into the design of the line structure. Extracts from reports of experience from various companies operating high-tension lines with special reference to insulation.

APPENDIX I, pages 119-122. Deterioration of Porcelain Insulators in Service, by J. A. Brundige. Cause of molecular fatigue and methods of detection.

APPENDIX II, pages 123-124. Radius of Influence of a Direct Lightning Stroke, by L. C. Nicholson.

APPENDIX III, pages 124-127. Transmission Line Problems in the West, by P. M. Downing. Brief notes on experience in operation.

APPENDIX IV, pages 127-129. Switching, by G. Faccioli. Effect of switching in producing oscillations.

THE PRESENT STATUS OF ALUMINUM-CELL LIGHTNING ARRESTERS

E. E. F. Creighton **Vol. xxxiii—1914, pp. 293-300**

Brief survey of the conditions of operation of aluminum-cell arresters. References to recent investigations of lightning phenomena and their possible effects upon the design of protective apparatus. Characteristics of aluminum-cell arrester including dielectric spark lag, dissolution of film, charging resistance, oscillations, damping surges due to natural operations. Characteristics of d-c. aluminum arrester.

Discussion, pages 301-308, by Messrs. V. Karapetoff, F. W. Peek, Jr., L. C. Nicholson, C. O. Mailloux, C. P. Steinmetz and E. E. F. Creighton.

Lightning and other high-voltage and high-frequency disturbances.

SOME INVESTIGATIONS ON LIGHTNING PROTECTION FOR BUILDINGS

L. A. DeBlois **Vol. xxxiii—1914, pp. 519-538**

Description of investigations conducted for a large manufacturer of explosives to determine upon a suitable system of lightning protection for buildings containing explosives.

An analysis by oscillograph of the secondary currents induced by actual lightning discharges in vertical earthed conductors. Tentative explana-

tion of the phenomena generally attributed to high-frequency oscillations by the existence of unidirectional waves of almost vertical front.

An investigation of the primary effects of a 20-in. spark in air having the same essential characteristics as those attributed to lightning when applied to a model protective system consisting of isolated vertical conductors surrounding a small building.

An investigation of the secondary effects produced under the above conditions.

Brief description of a general protective system recommended for explosives buildings.

Discussion, pages 536-544, by Messrs. E. E. F. Creighton, George R. Olshausen, A. G. Webster, Elihu Thomson, W. J. Humphreys, Trygve D. Yensen and L. A. DeBlois.

Remarks on the nature of lightning and lightning strokes.

EXPERIENCES WITH LINE TRANSFORMERS

D.W. Roper **Vol. xxxiii—1914, pp. 685-697**

Analysis of the transformer troubles for one year on a system having nearly 15,000 transformers installed. Curves showing the record of burn-outs of four different makes of transformers are used as a basis for a discussion of effect of the value placed on continuous service in the selection of transformers. The results of experiment with improved lightning protection are given, showing how the troubles were reduced.

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General remarks on design, operation and protection of transformer installations.

VOLTAGE TESTING OF CABLES

W. I. Middleton and Chester L. Dawes **Vol. xxxiii—1914, 1185-1206**

Analysis of e. m. f. stresses in insulation. Tests that must be made, followed by description of new type of oscillating voltmeter for measuring peak values.

Discussion, pages 1207-1215, by Messrs. W. A. Del Mar, C. O. Mailloux, Henry G. Stott, E. E. F. Creighton, Charles L. Fortescue, Percy H. Thomas, J. R. Craighead, W. I. Middleton and Chester L. Dawes.

General remarks on voltage testing of cables—what voltage, what sources. Cause of third harmonic disturbances and effect of peak e. m. f.

PROTECTIVE REACTORS FOR FEEDER CIRCUITS OF LARGE CITY POWER SYSTEMS

James Lyman, Leslie L. Perry and A. M. Rossman **Vol. xxxiii—1914, pp. 1509-1519**

Outline of the use and limitations of protective reactance coils in feeder circuits. Curves given showing what the effects of feeder reactors are, with and without bus reactors, for generators of various reactances. The advantages that might be gained by parallel operation of feeders are discussed and the difficulties to be encountered are pointed out.

Discussion incorporated with that of paper by J. L. McK. Yardley on "Use of Reactance with Synchronous Converters."

USE OF REACTANCE WITH SYNCHRONOUS CONVERTERS
An Insurance to Continuity of Service and a Protection to Apparatus.
J. L. McK. Yardley **Vol. xxxiii—1914, pp. 1521-1533**

Results of overload and short-circuit tests upon two synchronous converters of widely different operating characteristics in circuit with auxiliary reactors. In the one case the reactor is in the a-c. circuit and in the other in the d-c. circuit.

Division of synchronous converter installations into a few general classes with respect to the character and exactions of the service conditions under which they are required to operate with respect to the need of desirability of employing protective reactance, and also with respect to the general design or type of the reactor to be employed.

Discussion, pages 1534-1547, by Messrs. D. B. Rushmore, Philip Torchio, H. W. Buck, H. R. Summerhayes, J. J. Frank, N. W. Storer, George T. Hanchett, Carl J. Fechheimer, Mr. Woodward, Mr. Howard, Mr. Burnham, J. L. McK. Yardley and John B. Taylor.

General remarks on design and application of protective reactors.

15. DISTRIBUTION SYSTEMS

OUTDOOR VS. INDOOR SUBSTATIONS
Alexander Macomber **Vol. xxxiii—1914, pp. 57-63**

Brief review of the types of apparatus that have been developed for outdoor substation operation. Classification of outdoor substations according to application, and discussion of each. Relative merits of outdoor and indoor substations.

Discussion incorporated with that of paper by Leslie L. Perry on "Outdoor Substations in the Middle West."

OUTDOOR SUBSTATIONS IN NEW ENGLAND
Fred L. Hunt **Vol. xxxiii—1914, pp. 65-69**

Brief description and discussion of two substations of the Amherst Power Company, giving the basis of choice between the outdoor and indoor stations. Care of transformers and oil switches in freezing weather.

Discussion incorporated with that of paper by Leslie L. Perry on "Outdoor Substations in the Middle West."

INDOOR AND OUTDOOR SUBSTATIONS IN PENNSYLVANIA
H. L. Fullerton **Vol. xxxiii—1914, pp. 71-87**

General analysis of substations designed for primary voltages below 20,000. Both indoor and outdoor types considered, being classified under the heads: Customers' stations fed from distribution, customers' stations fed from transmission system, company's stations. Selection of location, type of building, apparatus, etc. Relative costs of different types of construction. General layouts for typical bus arrangements. Relative merits of outdoor and indoor stations.

Discussion incorporated with that of paper by Leslie L. Perry on "Outdoor Substations in the Middle West."

OUTDOOR SUBSTATIONS IN THE MIDDLE WEST
Leslie L. Perry **Vol. xxxiii—1914, pp. 89-91**

Experience with small high-tension substations installed out-doors on towers.

Discussion (including that of paper by Messrs. Alexander Macomber; Fred L. Hunt; and H. L. Fullerton), pages 92-103, by Messrs. A. H. Kruesi, A. R. Smith, Roy E. Argersinger, H. B. Gear, W. S. Moody, Allen M. Rossman, J. C. Smith, P. W. Sothman, J. Edward Kearns, K. C. Randall, Henson E. Bussey, E. A. Lof, Farley Osgood and Dugald C. Jackson.

Field for outdoor substations. Limitations of apparatus for outdoor substations.

DISTRIBUTION OF ELECTRICAL ENERGY

Report of Sub-Committee on Distribution

P. Junkersfeld, Chairman **Vol. xxxiii—1914, pp. 211-217**

General remarks on desirability of few large substations compared with many small ones. Bibliography of distribution for light, power and railways. Cables and underground construction.

APPENDIX I, pages 217-222. Three-Wire D-C. Distribution, by Philip Torchio. Brief review of practice.

APPENDIX II, pages 222-235. Alternating-Current Distribution, by H. B. Gear. Brief outline of practice for distribution of electric energy in bulk and also for general use. Typical circuits and networks. Demand factors. Advice for selection of apparatus for substations and distribution systems.

APPENDIX III, pages 236-240. Effect of Consumers' Apparatus and Wiring on Distribution, by H. Goodwin. Rules for governing consumers' load characteristics.

APPENDIX IV, pages 240-251. Direct-Current Distribution for Surface Railways—Urban Service, by R. H. Rice. General analytical discussion of the system including substations, feeders, working conductors and return.

APPENDIX V, pages 251-259. Direct-Current Distribution for Underground and Elevated Railways, by E. J. Blair. Working or contact conductor layout for different types of systems in actual use with special regard to feeding points and sectionalization.

APPENDIX VI, pages 259-261. Direct-Current Distribution for Interurban and Steam Railroads, by W. G. Carlton. Brief notes on various types and word about choice of working e.m.f.

APPENDIX VII, pages 261-262. A-C. Distribution for Interurban and Steam Railroads, by W. S. Murray. Recommendation of single-phase overhead construction.

APPENDIX VIII, pages 262-266. The Relation of Distribution Problems and Switching Apparatus, by E. B. Merriam. Brief discussion of factors most affected by switching, such as reliability of service, protection of system from disturbances, and safety of operators.

APPENDIX IX, pages 266-269. Distribution for Street Lighting Service, by Paul M. Lincoln. Advantages of constant current series system of distribution.

Discussion, pages 270-282, by Messrs. H. L. Wallau, Philip Torchio, S. D. Sprong, D. W. Roper, E. M. Hewlett, H. R. Summerhayes, John B. Taylor, E. W. Trafford, J. T. Kelly, Jr., John Murphy, H. B. Gear and Carl Schwartz.

General remarks on operation of distribution circuits and experience with control, protective and switching apparatus of various types.

MINE SUBSTATIONS
Their Construction and Operation

H. Booker **Vol. xxxiii—1914, pp. 439-444**

Brief practical discussion of layout, operation and maintenance of substations around coal mines. List of common defects in design of substations and faults in the organization of the operating force.

Discussion (including that of paper by Will M. Hoen), pages 445-449, by Messrs. W. A. Thomas, P. M. Lincoln, N. Stahl, and Will M. Hoen.

Use of synchronous converters in mines. Load characteristics of mines.

A DISTRIBUTION SYSTEM FOR POWER PURPOSES

F. D. Nims **Vol. xxxiii—1914, pp. 1299-1304**

Description of the distribution system of the Western Canada Power Company, Limited, touching on the overhead and underground systems in general. Advantages obtained by duplicating lines, both for eliminating outages and from a financial standpoint. Also the advantages obtained by using a steel-taped lead-armored cable placed directly in the ground, figures showing the exact cost of such an installation being given.

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16. CONTROL, REGULATION AND SWITCHING

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RECORDING DEVICES

Charles P. Steinmetz **Vol. xxxiii—1914, pp. 283-292**

Fundamental types of automatic recorders. Demonstration by practical examples of usefulness of automatic recorders in operation of electric systems. Use of multi-recorder.

No discussion.

MINE DUTY CONTROLLERS

Harrison P. Reed **Vol. xxxiii—1914, pp. 367-376**

Discussion of the advisable types of control to be used for various mining equipment, particularly in bituminous coal mines. Operating conditions are taken up in detail and proper control equipment suggested to meet these conditions.

Discussion, pages 376-384, by Messrs. F. L. Stone, Sidney G. Vigo, Graham Bright, H. H. Clark, H. D. James, W. C. Kennedy, C. J. E. Waxbom, W. M. Hoen and Arthur S. Biesecker.

General remarks on control, systems for mill work. Oil vs. air-break contactors. Explosion-proof cases for switches and motors.

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General remarks on the third harmonic in transformer operation.

CONCATENATED INDUCTION MOTORS FOR ROLLING MILL DRIVE

William O. Oschmann **Vol. xxxiii—1914, pp. 899-920**

Description of a six-speed concatenated induction motor set for driving the finishing rolls of a 12-stand continuous mill and analysis of the conditions that determined choice of prime mover and motor drive control. Load diagrams and power characteristics curves.

Discussion, page 921, by Messrs. Rudolph Tschentscher, T. E. Tynes and A. E. Averrett.

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17. TRACTION

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APPENDIX VI, pages 259-261. Direct-Current Distribution for Interurban and Steam Railroads, by W. G. Carlton. Brief notes on various types and word about choice of working e. m. f.

APPENDIX VII, pages 261-262. A-C. Distribution for Interurban and Steam Railroads, by W. S. Murray. Recommendation of single-phase overhead construction.

APPENDIX VIII, pages 262-266. The Relation of Distribution Problems and Switching Apparatus, by E. B. Merriam. Brief discussion of factors most affected by switching, such as reliability of service, protection of system from disturbances, and safety of operators.

APPENDIX IX, pages 266-269. Distribution for Street Lighting Service, by Paul M. Lincoln. Advantages of constant current series system of distribution.

Discussion, pages 270-282, by Messrs. H. L. Wallau, Philip Torchio, S. D. Sprong, D. W. Roper, E. M. Hewlett, H. R. Summerhayes, John B. Taylor, E. W. Trafford, J. T. Kelly, Jr., John Murphy, H. B. Gear and Carl Schwartz.

General remarks on operation of distribution circuits and experience with control, protective and switching apparatus of various types.

A COMPARISON OF THE TELEGRAPH WITH THE TELEPHONE AS A MEANS OF COMMUNICATION IN STEAM RAILROAD OPERATION

M. H. Clapp **Vol. xxxiii—1914, pp. 319-338**

Brief historical description of the use of telegraph and telephone on railroads. Description of typical railroad telegraph system. Cost and method of operation. Discussion of advantages and disadvantages of telegraph for railroad work. Description of typical railroad telephone plant, cost and method of operation, followed by discussion of advantages and disadvantages. Comparison of telegraph with telephone for handling railroad traffic and business.

Discussion (including that of paper by W. Lee Campbell), pages 339-351, by Messrs. William Maver, Jr., William E. Harkness, R. N. Hill, D. P. Grace, John B. Taylor, W. Lee Campbell, M. H. Clapp and Donald McNicol.

General remarks on use of telephone and telegraph on railroads. Use of composite telephone and telegraph circuits. Cost of phantom circuits. Speed and efficiency of telegraph compared with telephone.

THE DEVELOPMENT OF THE ELECTRIC MINE LOCOMOTIVE

G. M. Eaton **Vol. xxxiii—1914, pp. 403-414**

Evolution of coal mine locomotive with illustrations. Various types of mine locomotives, construction shown and briefly discussed. Also brief reference to various types of motors with different methods of lubrication and bearing construction. Design data plotted to show tendency of future development.

Discussion, pages 415-429, by Messrs. W. W. Miller, C. W. Beers, Carl J. E. Waxbom, Graham Bright, F. L. Stone, G. M. Eaton, L. J. Ilsey, W. A. Thomas, G. H. Shapter, E. H. Martindale and N. W. Storer.

General remarks on constructional features of mine locomotives. Data

on costs, repairs and troubles from actual experience. Experience with ball bearings.

DELTA AND Y CONNECTIONS FOR RAILWAY TRANSMISSION AND DISTRIBUTION

Cassius M. Davis **Vol. xxxiii—1914, pp. 807-810**

Brief statement of problem of selecting connections for railway system.

Discussion (including that of paper by T. S. Eden), pages 811-817, by Messrs. John B. Taylor, C. J. Fechheimer, E. G. Merrick, T. S. Eden, R. E. Doherty, Cassius M. Davis and Selby Haar.

Advantages of delta connection of alternators. Connection of turbo alternators.

THE ELECTRICAL OPERATION OF THE BUTTE, ANACONDA & PACIFIC RAILWAY

J. B. Cox **Vol. xxxiii—1914, pp. 1369-1393**

Review of engineering study and construction of the electrical installation of the Butte, Anaconda and Pacific Railway, giving reasons for using purchased energy and showing by curves and tables the savings accomplished over previous steam operation.

Discussion, pages 1394-1403, by Messrs. Paul Lebenbaum, C.P. Kahler, J. C. Ralston, A. A. Miller, W. K. Stacy and J. B. Cox.

Additional data on the repair of locomotives and the operation of collectors. Comparison of electric with steam locomotive repairs.

REPORT BY THE JOINT COMMITTEE ON INDUCTIVE INTERFERENCE TO THE RAILROAD COMMISSION OF THE STATE OF CALIFORNIA

Vol. xxxiii—1914, pp. 1441-1485

Brief account of the formation of the Committee, its activities and results accomplished and recommendations for rulings by the Railroad Commission of the State of California, together with a scientific technical discussion in explanation of the results and recommendations.

Discussion, pages 1486-1508, by Messrs. P. N. Nunn, J. B. Fisken, A. H. Halloran, A. J. Bowie Geo. S. Humphrey, J. C. Martin, L. J. Corbett, Chas. P. Kahler, L. T. Merwin, C. E. Rogers, A. J. Bowie, Jr., and A. H. Babcock.

Criticism and defense of the rules. Question of partisanship in the drafting of the rules.

GRAPHIC METHOD FOR SPEED-TIME AND DISTANCE-TIME CURVES

E. C. Woodruff **Vol. xxxiii—1914, pp. 1673-1676**

Description of a simple method for obtaining speed-time and distance-time curves, which avoids the usual step-by-step process.

Discussion, pages 1677-1719, by Messrs. Selby Haar, C. O. Mailloux, N. W. Akimoff, F. Castiglioni, F. E. Wynne, N. W. Storer, E. C. Woodruff and D. D. Ewing.

Resume of the Mailloux method of calculating and plotting speed-time and curves and comparison with the author's method. Equation for practical motor acceleration curves. Use of speed-distance curve for finding cutting off point. Use of slide rule for motor characteristic curves in speed-time curve calculations and determination of the capacity of railway motors. Castiglioni method compared with Mailloux method of speed-time calculations.

18. LIGHTING AND LAMPS

SELF-CONTAINED PORTABLE ELECTRIC MINE LAMPS

H. O. Swoboda — Vol. xxxiii—1914, pp. 385-396

General requirements of safety lamp for mines. Description of construction of groups of prize-winning electric lead storage battery safety lamps. Method of caring for lamps and batteries. Cost of operation.

Discussion, pages 397-401, by Messrs. H. H. Clark, H. H. Smith, R. C. Burrows, and H. O. Swoboda.

Advantages of the alkaline battery.

19. ELECTRICITY IN THE ARMY AND NAVY

ELECTRICITY THE FUTURE POWER FOR STEERING VESSELS

H. L. Hibbard — Vol. xxxiii—1914, pp. 619-648

Brief description of steam steering gear and recital of disadvantages, followed by advantages of electric system. Brief historical resume of electric steering gear installations. Description of installations on battleship *Texas*, giving calculations of horse power and results of tests. Actual recording ammeter curves.

Discussion, pages 649-657, by Messrs. G. A. Pierce, Jr., Mathias Pfatischer, Maxwell W. Day, R. A. Beekman, H. L. Hibbard and H. A. Hornor.

Early installations on Russian warships. Defense of Pfatischer electric steering system. Advantages of motor-generator steering systems. Disadvantages of contactor type of electric steering gear.

THE FUTURE OF ELECTRIC HEATING AND COOKING IN MARINE SERVICE

H. J. Mauger — Vol. xxxiii—1914, pp. 659-668

General remarks on use and future of electric cooking on board ship.

Brief description of equipment of battleship *Texas* and results of tests of power consumption. Advantages of electric cooking and heating.

Discussion, pages 669-672, by Messrs. W. S. Hadaway, E. F. Dutton, H. J. Mauger and Frank T. Leilich.

Disadvantages of electric cooking on board ship. Difficulties of building resistors for high surface temperatures.

ELECTRIC HEATING AS APPLIED TO MARINE SERVICE

C. S. McDowell and D. M. Mahood — Vol. xxxiii—1914, pp. 839-850

A comparison of convection and radiant heaters, the proper use of each type being shown, for space heating on shipboard with metal decks and bulkheads.

Curves showing results obtained on tests to determine the best type of heater for shipboard and desirable features of heater are indicated.

Discussion, pages 851-855, by Messrs. W. S. Hadaway, Jr., Alfred E. Waller, Charles D. Knight, D. B. Rushmore, F. C. Caldwell, D. M. Mahood, and H. A. Hornor.

Results of electric heating tests at the University of Nebraska. Relative merits of open-coil and enclosed heater units.

THE ELECTRICALLY DRIVEN GYROSCOPE IN MARINE WORK

H. C. Ford — Vol. xxxiii—1914, pp. 857-871

Definition of gyroscope and brief statement of practical uses to which it has been put.

A general description of the gyro-compass as adopted by the United States Navy for use on all the battleships and submarine vessels, and of

the many electrical and mechanical devices that have been developed by E. A. Sperry to perform the various functions whereby an instrument of great precision has been secured.

Brief mention of large gyroscopes which are capable of counteracting enormous wave forces and completely stabilizing any ship against rolling in the heaviest seas.

Discussion, page 872, by Messrs. Alfred E. Waller and H. C. Ford.

Remarks on stabilizing action of gyroscope.

SUBMARINE SIGNALING

The Protection of Shipping by a Wall of Sound and Other Uses of the Submarine Telegraph Oscillator

R. F. Blake — **Vol. xxxiii—1914, pp. 1549-1561**

Dangers of the sea. Outline of development of underwater signaling. Description of Fessenden oscillator and uses to which it may be put. Report of Capt. Quinan on equipment of U. S. revenue cutter *Miami*.

Discussion, pages 1562-1565, by Messrs. W. S. Franklin, H. J. W. Fay, Elmer A. Sperry, G. A. Hoadley, H. A. Hornor, George Breed, John B. Taylor and J. L. Woodbridge.

ELECTRICAL EQUIPMENT OF THE ARGENTINE BATTLESHIP "MORENO"

H. A. Hornor — **Vol. xxxiii—1914, pp. 1567-1592**

Description of the electrical installation of one of the two Argentine battleships building in this country. The methods of installation and distribution of energy, and the results secured by departure from present practise.

Detailed descriptions are given of important and unusual equipments such as steering gear, anchor windlass, searchlights, gyro-compass, etc., etc.

Discussion, pages 1593-1608, by Messrs. H. L. Hibbard, Maxwell W. Day, G. A. Pierce, Jr., Elmer A. Sperry, B. B. Bierer, J. H. Linnard, W. F. Cochrane, Clyde S. McDowell, L. C. Porter and H. A. Hornor.

General remarks and comments on electrical installation practise for the navy.

20. MISCELLANEOUS APPLICATIONS OF ELECTRICITY

SOURCES OF DIRECT CURRENT FOR ELECTROCHEMICAL PROCESSES

F. D. Newbury — **Vol. xxxiii—1914, pp. 1-13**

Brief statement of the requirements of generators for heavy-current low-voltage service. Discussion of relative merits of the various types of generator units suitable for electrochemical work, giving the limiting features of each type of generator and prime mover. Comparative efficiency and cost of various systems.

Discussion, pages 13-22, by Messrs. G. A. Roush, F. A. Lidbury, F. L. Antisell, J. B. F. Herreshoff, C. O. Mailloux, Lawrence Addicks, C. H. Vom Baur, H. E. Longwell, F. D. Newbury and F. W. Harris.

Typical size of units for electrochemical plants. Current density and other data in copper deposition. Economy of various types of prime movers.

MINE DUTY CONTROLLERS

Harrison P. Reed — **Vol. xxxiii—1914, pp. 357-375**

Discussion of the advisable types of control to be used for various mining equipment, particularly in bituminous coal mines. Operating

conditions are taken up in detail and proper control equipment suggested to meet these conditions.

Discussion, pages 376-384, by Messrs. F. L. Stone, Sidney G. Vigo, Graham Bright, H. H. Clark, H. D. James, W. C. Kennedy, C. J. E. Waxbom, W. M. Hoen, and Arthur S. Biesecker.

General remarks on control systems for mill work. Oil vs. air-break contactors. Explosion-proof cases for switches and motors.

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General remarks on constructional features of mine locomotives. Data on costs, repairs and troubles from actual experience. Experience with ball bearings.

MINE SUBSTATIONS

Motor-Generator Sets vs. Synchronous Converters

Will M. Hoen **Vol. xxxiii—1914, pp. 431-437**

Comparison of synchronous converters, synchronous motor-generators and induction motor-generators as to starting characteristics, efficiency and performance on mine loads.

Discussion incorporated with that of paper by H. Booker on "Mine Substations—Their Construction and Operation."

MINE SUBSTATIONS

Their Construction and Operation

H. Booker **Vol. xxxiii—1914, pp. 439-444**

Brief practical discussion of layout, operation and maintenance of substations around coal mines. List of common defects in design of substations and faults in the organization of the operating force.

Discussion, (including that of paper by Will M. Hoen), pages 445-449, by Messrs. W. A. Thomas, P. M. Lincoln, N. Stahl and Will M. Hoen.

Use of synchronous converters in mines. Load characteristics of mines.

MAGNETIC AND OTHER PROPERTIES OF ELECTROLYTIC IRON MELTED IN VACUO

Trygve D. Yensen **Vol. xxxiii—1914, pp. 431-475**

Brief mention of early work done in the study of magnetic properties of iron and iron alloys. Description of the construction of vacuum furnace for melting iron and permeameter for testing short bars. Account of methods of preparing specimens and testing their magnetic properties. Effect of heat treatment on magnetic properties shown by curves and tables. Discussion of equilibrium diagram of iron-carbon alloys with special reference to magnetic properties.

No discussion.

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EFFECT OF ELECTROLYSIS ON THE COMPRESSIVE STRENGTH OF CEMENT AND CONCRETE

C. Edward Magnusson and B. Izhuroff **Vol. xxxiii—1914, pp. 673-684**

Results of prolonged tests to corroborate results given in former paper (Vol. XXX, page 2055). Description of apparatus and tabulation of results.

No discussion.

ELECTRIC HEATING AS APPLIED TO MARINE SERVICE

C. S. McDowell and D. M. Mahood **Vol. xxxiii—1914, pp. 839-850**

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Discussion, page 872, by Messrs. Alfred E. Waller and H. C. Ford.

Remarks on stabilizing action of gyroscope.

DIRECT-CURRENT MOTORS FOR COAL AND ORE BRIDGES

R. H. McLain **Vol. xxxiii—1914, pp. 873-884**

Brief description of the mechanical arrangement of a coal bridge. Performance characteristic curves and discussion of type of motors suited to the work and the proper methods of gearing the motor for most economical results.

Discussion, pages 885-886, by Messrs. D. B. Rushmore, S. C. Lindsay, T. E. Tynes and R. H. McLain.

CONCATENATED INDUCTION MOTORS FOR ROLLING MILL DRIVE

William O. Oschmann **Vol. xxxiii—1914, pp. 899-920**

Description of a six-speed concatenated induction motor set for driving the finishing rolls of a 12-stand continuous mill and analysis of the conditions that determined choice of prime mover and motor drive control. Load diagrams and power characteristic curves.

Discussion, page 921, by Messrs. Rudolph Tschentscher, T. E. Tynes and A. E. Averrett.

STERILIZATION OF WATER BY ULTRA-VIOLET RAYS OF THE MERCURY-VAPOR QUARTZ LAMP

M. von Recklinghausen **Vol. xxxiii—1914, pp. 1217-1230**

Sources, measurement and properties of ultra-violet light. Reference to development of mercury lamp water sterilizers and the development of pistol lamps for large sterilizing units.

Description of two typical installations, one in Europe, one in America.

Data on the power consumption for the sterilization of water by ultra-violet rays.

Discussion, pages 1231-1242, by Messrs. Morgan Brooks, Theodore A. Leisen, William B. Jackson, M. von Recklinghausen, Alfred Jerz and A. E. Walden.

General remarks on the sterilization of water by ultra-violet rays and ozone gas. Operating results with ozone gas plant.

ELECTRICITY IN THE LUMBER INDUSTRY

E. F. Whitney **Vol. xxxiii—1914, pp. 1315-1354**

Description of the lumbering industry as carried on in Washington and Oregon, and the application of electric power to the various operations carried on under the two main divisions of logging and milling. Typical applications illustrate types of motors and power transmission equipments, and the average power demands of the various logging operations and milling processes. In addition to the machines used in ordinary sawmill work, those used in planing mills and shingle mills are described. The question of the disposition of waste is considered, and comparative fuel values are given. The illustrations show logging operations and electrically driven saws, finishing machinery and lumber-handling machinery in the Pacific Coast lumber districts.

Discussion, pages 1355-1367, by Messrs. Scott, A. A. Miller, F. D. Weber, J. B. Fisken, L. T. Merwin, Mr. Cheek, A. Norman, W. H. R. Fraser, John Harisberger and E. F. Whitney.

Practice in electric operation of saw mills.

APPLICATION OF ELECTRIC MOTORS TO GOLD DREDGES

Girard B. Rosenblatt **Vol. xxxiii—1914, pp. 1405-1416**

Classification of gold dredges and outline of requirements for electric operation. Choice of motor and specifications for design of digging motor.

Discussion, pages 1417-1427, by Messrs. Ford W. Harris, M. H. Gerry, Jr., F. A. Ross, L. K. Armstrong, W. M. Shepard, A. A. Miller and G. B. Rosenblatt.

Experience with electric dredges.

ELECTRICAL FEATURES OF THE U. S. RECLAMATION SERVICE

F. H. Newell **Vol. xxxiii—1914, pp. 1609-1634**

Brief outline of electrical development problems of the Reclamation Service, followed by short descriptions of the chief developments. Tabulated data on the electrical installations and power plants of the Reclamation Service.

Discussion, pages 1625-1629, by Messrs. Paul Spencer, Ralph W. Pope, J. E. Kershner, P. M. Lincoln, H. A. Hornor, Vladimir Karapetoff, Carl Hering, Mr. Bender, H. Goodwin, Jr. and F. H. Newell.

General remarks on the cost of energy for hydroelectric developments.

21. TELEPHONY AND TELEGRAPHY

TRAFFIC STUDIES IN AUTOMATIC-SWITCHBOARD TELEPHONE SYSTEMS

W. Lee Campbell **Vol. xxxiii—1914, pp. 309-318**

Methods of observing traffic. Description of traffic-recording machine. Relative efficiency of trunk groups as shown by traffic recorder. Study of loads and determination of grouping of trunks. Charts and equations.

Discussion, incorporated with that of paper by M. H. Clapp on "A Comparison of the Telegraph with the Telephone as a Means of Communication in Steam Railroad Operation."

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General remarks on use of telephone and telegraph on railroads. Use of composite telephone and telegraph circuits. Cost of phantom circuits. Speed and efficiency of telegraph compared with telephone.

EXPERIENCE OF PACIFIC GAS AND ELECTRIC CO. WITH THE GROUNDED NEUTRAL

J. P. Jollyman, P. M. Downing and F. G. Baum **Vol. xxxiii—1914, pp. 767-772**

Outline of the distributing system of the Pacific Gas and Electric Company of California which operates at 60 kv., the transformers being Y-connected, with the neutrals solidly grounded.

Discussion (including that of papers by Louis F. Blume and Charles Fortescue), pages 773-802, by Messrs. Guido Semenza, F. F. Brand, W. W. Lewis, V. M. Montsinger, C. M. Davis, L. F. Blume, H. S. Osborne, F. E. Haskell, H. S. Osborne, C. O. Mailloux, E. E. F. Creighton, John B. Taylor, F. C. Green, P. M. Lincoln, D. W. Roper, F. W. Peek, Jr., J. R. Werth, C. L. Fortescue and Max H. Collbohm.

Summary of transformer connection practice in Italy. Classification of high tension transmission systems of the world on basis of star and delta. Operating results of six great transmission systems. Results of tests on effect of capacity and inductance upon third harmonics in star auto-transformers. Comparison of star and delta from point of view of telephone disturbances. The problem of insulating transmission lines.

A HIGH-SPEED PRINTING TELEGRAPH SYSTEM

Carl Kinsley **Vol. xxxiii—1914, pp. 1243-1253**

Description of a system of high-speed printing telegraphy devised by the author. Brief mention of a number of high-speed systems which have been tested by the operating companies, none of which have completely fulfilled all the requirements for accuracy, rapidity and low cost desirable for commercial work.

Discussion, pages 1254-1261, by Messrs. C. R. Underhill, Ralph W. Pope, George S. Macomber and Carl Kinsley.

Underhill printing telegraph. Additional information on the Kinsley system.

TOLL TELEPHONE TRAFFIC

An Experimental Study of the Relationship between Circuit Loads and Delay to Traffic.

Frank F. Fowle **Vol. xxxiii—1914, pp. 1263-1270**

Description of experiments to determine the relationship between telephone circuit loads and the corresponding delay to traffic.

Discussion, pages 1271 and 1272, by Mr. J. Lloyd Wayne, 3rd.

REPORT BY THE JOINT COMMITTEE ON INDUCTIVE INTERFERENCE TO THE RAILROAD COMMISSION OF THE STATE OF CALIFORNIA

Vol. xxxiii—1914, pp. 1441-1488

Brief account of the formation of the Committee, its activities and results accomplished and recommendations for rulings by the Railroad Commission of the State of California, together with a scientific technical discussion in explanation of the results and recommendations.

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Criticism and defense of the rules. Question of partisanship in the drafting of the rules.

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22. MISCELLANEOUS TOPICS

THE EVOLUTION OF THE INSTITUTE AND OF ITS MEMBERS

President's Address

C. O. Mailloux **Vol. xxxiii—1914, pp. 817-838**

STANDARDIZATION RULES

Vol. xxxiii—1914, pp. 1787-1883

ANNUAL REPORT OF THE BOARD OF DIRECTORS

Vol. xxxiii—1914, pp. 1895-1931

TOPICAL INDEX

Abbreviations list 1798
Acceleration curves, commercial practice, analysis 1697
Air, dielectric strength 613
effect of frequency 951
investigation 951
Alabama Interstate Power Co., data on transformer connections, voltage and capacity 765
Alkaline batteries. (See Batteries.)
Alternators. (See Generators A-C.)
Altitude, relation to air density 1728
pressure 1729
Aluminum, cables. (See Cables.)
elastic limit 107
wire. (See Wire.)
Amberite, surface resistance 1749
Amherst Power Co., outdoor power stations 65
Ammeter, contact making 890
definition 1805
recording, definition 1805
Anchor windlass, power requirements, battleship *Moreno* 1579
Anemometer, electric 1584
Appalachian Power Co., data on transformer connections, voltage and capacity 765
pole design 1058
transmission report 1015
Arc, mercury vapor 1667
welding. (See Welding.)
Archoid for motor acceleration 1696
Armatures, current density 361
flux density 361
Ash handling equipment, cost 204
Au Sable Elec. Co., data on transformer connections voltage and capacity 765
isolated delta experience 777
Austenite, definition 467
Auto transformers. (See Transformer Auto.)
Balancer, definition 1800
Base energy, definition 168
Batteries, bibliography 217
d. c. wiring diagram 220
storage, alkaline compared with lead 426
disadvantages 401
operation cost vs. lead 426
vs. lead 398
d. c. distribution station 221
electrode life 395
for mine lamps operation, cost 395
for portable lamps 389
lead, operation cost vs. alkaline 398 426
mine locomotive 425

Battleship, applications of electric energy 1574
Moreno, electrical equipment 1569
Texas, electric cooking test 662
steering gear, description 630
electric power tests 640
power calculations 634
Bearing, ball, for mine locomotives 410
for mine locomotives 410, 419, 421, 423 424
roller, for mine locomotives 410
Beeswax, surface resistance, tests 1753
Bell, submarine 1552
Bibliography, batteries 217
cables 216
distribution for electric railways 215
light and power 215
Standardization Rules 1883
sub-stations 217
transmission systems 1103
underground construction 216
Big Creek, transmission line, data 1291
system, description 1283
equipment data 1290
history 1289
Booster, definition 1800
Boilers, cost 204
oil firing, cost 1178
plant, cost 204
Braking, dynamic, with series motor 879
Brightness, definition 1866
Broilers, electric power consumption 663
Brushes, contact drop, Standardization Rules 1826
current density 361
Buildings metallic, risk from lighting 531
red brick, cost 80
rock faced brick and sawed stone, cost 80
steel and concrete slab, cost 80
corrugated iron, cost 80
Bushings spark-over voltages effect of altitude 1721
Buses. (Also see Busbars.)
e. m. f. differences 33
ring and transfer connections 36
standard arrangements 26
Bushing, 85,000-volt design 1063
Butte, Anaconda & Pacific Ry. locomotive, description 1377
map of electric lines 1370 1372
operation, electric 1169
delays, investigation 1382
steam, delays, investigation 1382
power plants location 1374
profiles 1373
Cable, aluminum, elastic limit 1293
steel core, elastic limit 1293
tensile strength 1293
weight 1293
tensile strength 1293
Cables, aluminum, wind deflection for different sizes 132
weight 1293
armored, laid direct in ground, cost 1303
experience 1307
specification 1304
use on battleships 1601

Cables (*continued*)
bibliography 216
capacitance, Standardization Rules 1853
copper, wind deflection for different sizes 132
definition 1846
electrical tests, Standardization Rules 1850
factor-of-assurance 1207
safety 1196
fault, location 1311
heat, dissipation 1305
insulation resistance, Standardization Rules 1852
laying in ground 1303
locating faults 278
low-voltage, recommended test 1194
standard stranding 1848
Standardization Rules 1846
steel, elastic limit 1293
tensile strength 1293
weight 1293
subways, designing 218
temperature limitations, Standardization Rules 1850
terms, definition 1847
testing maximum voltage, effect of third harmonic 1212
three-core, maximum sizes in use 225
underground, service connections 218
voltage stress, effect of conductor diameter 1187
stresses formula 1186
testing 1185
apparatus 1198
voltage tests method of making 1197
recommended values 1208
Standardization Rules 1190
Candle, definition 1865
power, definition 1865
Capacitance, definition 1853
Capacity, definition 1798
Cars, baggage, weight 1381
passenger, weight 1381
Cedar river, water analysis 674
Celluloid, surface resistance, tests 1749
Cement, chemical analysis 674
compressive strength, effect of electrolysis 680
salt water mixture 680
effect of electrolysis 680
effect of electrolysis on strength 673
electrolysis, tests 674
physical analysis 674
Cementite, definition 467
Central Colo. Power Co., data on transformer connections, voltage and capacity 765
Ceresin, surface resistance 1753
Chili Exploration Co., data on transformer connections, voltage and capacity 765
transmission report 1015
Chippewa Valley Ry. Lt. & Pwr. Co., transmission report 1016
Circuit, constant-current, advantages 268
natural frequency 139
telephone and telegraph, Standardization Rules 1874
Circuit-breakers 264
automatic recorder, operation 289
definition 1854
outdoor substations 59

Circuit-breakers (*continued*)
quick acting, time opening 1547
opening, performance 1529
Standardization Rules 1854
Crest factor, definition 1794
Crossarms, life, practise 1047
steel, design Miss. Power Co. 1060
Current, alternating, definition 1793
at absolute zero test 1004
collectors. (See Trolleys.)
collection, trolleys. (See Trolleys.)
density, carbon brushes 361
converter armatures 361
copper deposition 17
direct, definition 1793
oscillating definition 1793
pulsating, definition 1793
residual analysis 1461
causes 1464
definition 1447
prevention 1469
short-circuit, calculation 44
formula, inductive circuit 51
maximum 49
sinusoidal, definition 1793
voice, frequency 1459
Cycle, definition 1793
Cymometer, definition 1125
Coal bridge hoist, power requirements 880
hoisting speed 880
power requirements 873
rack motor controller 879
power requirements 877
trolley power requirements 874
handling equipment, cost 204
mines. (Also see Mines.)
hoist control 373
locomotive controllers 372
pump motor control 371
uses for motors 368
ventilation fan motor control 369
Colorado Pwr. Co., experience, isolated delta 777
Committee Inductive Interference, definitions of terms 1446
early work 1442
future work, outline 1457
list of reports 1482
membership 1507
report, Calif., criticism 1487
report to Railroad Commission of California 1441
Institute. (See Institute.)
Rubber Insulation Manufacturers and Users of Rubber Compounds, report 1767
Communication circuit, definition 1446
Commutation, heavy currents 2
Commutator, construction 3
machines, classification 1801
slotting practice 427
Compensator, d. c., definition 1800
Concrete, effect of electrolysis on strength 672
electrolysis test 674

Condenser, aluminum cell 297
calibration 962
cost 204
variation with frequency 962
Condensing tunnels, cost 204
Conductors, definition 1846
deterioration 1090
explanation 1095
for long spans 109
steel-core aluminum, experiment 142
stranded, definition 1846
with zero resistance 1004
Connecticut River Transmission Co., data on transformer connections, voltage and capacity 760
Contactors for mine service 376
Control, by concatenation, wiring diagram 926
pump motors for mines 371
fan motor 369
hoist 372
equalizer system 373
rolling mills, by concatenation 913
Controllers, explosion proof 371 381
locomotives for mines 372
mine duty 367
moisture proof 371
Converter, cascade, definition 1801
d. c., definition 1801
definition 1800
frequency, definition 1801
phase, definition 1801
synchronous, 60-cycle modern practice 353
commutation, heavy currents 2
commutating pole effect on output 354
definition 1801
drooping, characteristic method of obtaining 1528
efficiency 358, 362 434
field dampers practice 356
flash-over test 262
large sizes 226
oscillation period 357
over-compounding feature 446
performance on mine loads 436
protection against short circuits 1524
protected with quick acting breaker and recorder 1531
reactance in leads, tests 1543
six-phase, heating 355
specification 360
starting conditions 434
use with reactors 1521
vs. motor-generators 431
for mine service 445
Cooking, electric, advantages 665
battleships equipped 662
compared with gas 672
costs 672
disadvantages 671
navy practice 659
top surface, power consumption 669
gas flame, power production 670
oil, cost 672

Copper, cables. (See Cables.)
conductivity, Standardization Rules 1850
elastic limit 107
electrolytic, cost 19
deposition, data 16 17
thicknesses 17
wire (See Wire.)
Cord, definition 1847
Corona, cause of wire vibration 1669
d. c., apparatus for test 1633
between parallel wires 1662
copper wire 1641
effect of ionization 1655
moisture 1651
pressure 1646 1649
temperature 1653
wire diameter 1639
material 1653
formula 1654
low pressures 1662
silver wire 1640
study 1631
d. c., variation in appearance 1644
e. m. f. measurement 955
effect of air density 599
frequency 952
energy distance equation 614
high-frequency 608
investigation at various frequencies 954
ionization by impact theory, application 600
losses a. c. formula 1670
d. c. formula 1670
negative characteristic 1658
oscillograph, use of milliampere series transformer 582
parallel wires, effect of spacing explanation 601
theory 589 610
visual, Peek's law, derivation 612
Cost, ash handling equipment 204
blast furnace gas 1174
boilers 204
coal handling equipment 204
condensers 204
condensing tunnels 204
cooking electric 672
oil fuel 672
copper, deposition 19
energy, d.c. vs. a. c. converted to d. c 11
Diesel engines, different sizes 1152
energy, electric, effect of load-factor 1159 1161
oil engines 20
on board ship 850
production 1178
steam engines 20
turbines 20
hydroelectric, calculation 184
production, effect of load factors 1178 1180
engineering, power plant construction 204
engines, gas 1169–1178 1181
different sizes 1148
operation 1178
oil 1175–1178–1180 1181
different sizes 1154
gas production, various conditions 1174

Cost (*continued*)
foundations, buildings 80
hydroelectric development 166
investigation, power plants 196
laying armored cable 1303
locomotives, electric, operation 1392
mine, parts 418
steam operation 1392
logging 1317 1319
railways, electric, operation 1323
steam, operation 1323
natural gas 1174
oil crude 1181
oscillograph 1481
piping 204
power plant buildings 204
hydroelectric 180
production, power plants 196
railroad telegraph plant 323
telephone plant 330
saw-mills, refuse burners 1344
stokers 204
switches, power plant equipment 204
telegraph line construction 322 341
telephone portable 331
line construction 329 341
towers, structural steel 80
transformers cases 694 695
operations 694 695
repairs 694 695
turbines, steam 1141 1181
operation 1178
turbo-generators 204
water sterilization, ozone 1237
ultra-violet light 1234
wiring, saw mills 1364
wood impregnation 1046
Counter-clockwise convention, definition 1794
Damping constant, definition 1872
Deficiency, definition 156
hydroelectric design, calculations 156
Degree, magnetic, definition 1797
Demand, definition 359 1796
factors, apartments 235
churches 235
definition 1796
homes 235
hospitals 235
hotels 235
manufacturing 235
offices 235
small stores 235
Depreciations, locomotive electric 1392 1399
power plants 183
steam-electric machinery 202
Dielectric strength, various material (See name of Material.)
tests, standard voltages 1829
Standardization Rules 1828
voltage measurement, Standardization Rules 1831
Distance-time curves, graphic methods 1673
Mailloux method 1679
Distortion factor, definition 1794
Diversity factor, definition 1797

Distribution, 12,000-volt, operation 1300
a. c. system 222
bulk supply 222
construction practice 235
frequency choice 223
general service 228
polyphase, circuit layout 231
secondary mains 232
single-phase, circuit layout 232
substation supply 222
transformer selection 234
armored cables, laid direct in earth 1307
cost 1303
circuits, battleship *Moreno* 1572
d. c. surface railways 240
three-wire 217
standard voltages 219
feeders, protective reactors 1509
heavy currents 4
light and power, bibliography 215
motor service 236
power circuits, battleship *Moreno* 1576
practice, report 211
railway a.c 261
bibliography 215
choice of connections 809
definition 1858
elevated 251
fourth rail 202
interurban 259
positive feeder system 241
purchased energy, choice of connections 808
return insulated 250
system design 249
sectionalizing methods 254
star and delta connections, choice 807
steam lines 259
system maintenance, cost 1398
third rail 253
three-wire 252
trolley line construction 244
underground 251
relation of consumer's apparatus to charges for service 239
service, protection problem 263
shipboard, voltage 1593 1595
street lighting 266
service maintenance problems 262
system, battleship *Moreno* 1569
effect of consumer's apparatus and wiring 236
Western Canada Pwr. Co., description 1299
Dredges, digging motor requirements 1411
dipper, power requirements 1408
elevator, digging motor 1412
bucket chain, power consumption 1410
power requirements 1408
gold, classification 1408
electric drive, advantages 1406
motor application 1405
operating conditions 1419
power requirements 1406
squirrel cage vs. slip-ring motors 1422
suction, power requirements 1408

Dynamometer, definition 1800
Ebro Irrigation Pwr. Co., data on transformer connections, voltage and capacity 765
Economics, water turbines 1163
prime movers 1158
Efficiency, conventional, definition 1821
converters, synchronous 8, 9, 358, 362 434
definition 1798
gearing for turbines 9
generators, a. c., ... 9
d. c. heavy current 9
unipolar 9
machine definition 1821
motor-generators 8
plant, definition 1821
power plants 194
railway motors 1862
Rankine cycle, steam turbines 1138
relation to heat consumption 1164
sub-station 358
thermal, Diesel engines 1150
gas engines 1135
locomobiles 1183
oil engines 1149 1150
various prime movers 1165
transformers 10
turbines, steam 1135
water 1155
Francis type 1157
water wheels 10
Electrochemistry, power sources, comparative efficiencies 9, 10 14
size of unit 13
sources of direct current for processes 1
Electrolysis, cemented-in metal pins of line insulators 1434 1435
effect on strength of concrete and cement 673
tests of cement and concrete 674
Electromagnets. (See Solenoids.)
Electrometer, disk, connection formula 1635
E. m. f., average value, measurement 957
effective value, measurement 961
high, effective actual measurement 1005
measurement, precautions 996
with air-gap 923
sphere-gap 923
maximum value, measurement 957
measurement, peak value 1204
with sphere-gap 945
residual, analysis 1461
causes 1464
definition 1447
prevention 1469
rise due to switching, equation 139
Energy, electric, applications in battleship *Moreno* 1574
cost, determination 193
in steam station, various load-factors 188
of production, oil engines 20
steam engines 20
turbines 20
cost on board ship 850
production cost 1181
dielectric field 139
magnetic field 138
production, d. c., cost vs. a. c. converted to d.c 11
efficiency, over-all 194

Engineering, power plant construction, cost..... 204
Engineers, social and civic evolution..... 826
Engine, Diesel, cost, different sizes..... 1152
equipment of battleship *Moreno*..... 1569
thermal efficiency..... 1150
weight, different sizes..... 1151
gas, blast furnace, cost..... 1169
practice..... 1167
capacity limitations..... 1143
cost, ...1169, 1178 1181
different sizes..... 1148
efficiency characteristic..... 1144
Ford Motor Co., installation..... 1170
fuel consumption..... 1145
maximum size..... 1142
operation cost..... 1178
overload capacity..... 1169
thermal efficiency..... 1145
weights, different sizes..... 1146
oil, capacity limitations..... 1149
cost.....1175, 1178 1181
different sizes..... 1154
equipment, battleship *Moreno*..... 1568
fuel consumption..... 1150
operation..... 1778
thermal efficiency.....1149 1150
weight, different sizes.....1151 1153
revolution indicator, electric..... 1584
steam, triple-expansion, steam consumption..... 20
Exciters, connection for automatic a.c. voltage regulation..... 1285
zero regulation..... 1284
Exposure, definition..... 1866
Factor-of-assurance, definition..... 1207
Factor, reactive, definition..... 1795
Feeders, calculation..... 247
parallel operation, effect of reactors..... 1516
protection..... 279
protective reactors..... 1509
quick automatic switches..... 278
railway, allowable drop..... 247
design, comments..... 245
reactors, early use..... 1535
Ferrite, definition..... 467
Field, electric, cylindrical conductor..... 591
logarithmic distribution..... 611
parallel, wires, exploration curve..... 1664
surface gradient equation..... 597
surface of wires..... 1632
Flux density, converter core..... 361
series transformer..... 577
luminous, definition..... 1865
Form factor, definition..... 1794
Foundations, concrete, cost..... 80
transmission towers..... 107
Frequency, definition..... 1793
high, advantages insulator testing..... 1129
characteristics e. m. f. from arc generator..... 982
measurement..... 1125
testing e. m. f. generation..... 974
vibration of conductors..... 971
leading transmission systems, table..... 765
natural, electric circuit..... 139
voice currents..... 1459

Furnace, vacuum 453
Fuses, definition 1855
Standardization Rules 1855
Gas, blast furnace, cost 1174
conduction, investigation with milliampere series transformer 585
flame, power production for cooking 670
natural, cost 1174
producer plant, labor, cost 1174
production cost, various conditions 1174
Gearing, turbines, efficiency 9
Gears, solid vs. split 428
turbine-driven units, efficiency 9
Generators, a.c., delta circulating current. characteristics 813
connection, advantages 811
efficiency 9
high-frequency 953
induction type, advantages 8
star and delta connections, relative merits 803
star connection, advantages 803
third harmonic, reduction factor 728
d. c., commutation, heavy currents 2
double-commutator 3
efficiency 9
maximum current output 3
turbine-driven for heavy currents 6
unipolar, turbine-driven 6
definition 1800
designed for Navy 606
double-current, definition 1800
high-frequency 974
life 202
reactance 24
Georgia Ry. & Pwr. Co., data on transformer connections, voltage and capacity 765
Glass, surface resistance, tests 1750
Glyptol, surface resistance 1749
Grand Rapids Muskegon Pwr. Co., data on transformer connections voltage and capacity 765
Grand Falls Wtr. Pwr. & Townsite Co., data on transformer connections voltage and capacity 760
Great Western Power Co., data on transformer connections, voltage and capacity 765
experience with isolated delta 776
tower design 1055
transmission report 1014
Ground wire, advantages 1760
effectiveness, experience 1038
in protection of transmission lines 110
support 1062
design 1082 1083
Grounded neutral, advantages operation of transmission system 770
transmission line 769
with transformers 769
auto-transformers 749
effect of resistance 743
on ground 741
residual current, test 1471 1473
e. m. f. and current 1465
telephone and telegraph disturbances 771
experience, Pacific Gas & Elec. Co. 767
Gyroscope, compass, Anschütz type 1588
battleship *Moreno* 1588

Gyroscope, compass (*continued*)
description 1597
precession, demonstration 861
Sperry type 862 1598
typical equipment 864
U. S. Navy 860
discovery 868
early serious application 858
for rolling ships 872
practical applications 859
stabilizing cars, first 859
S. S. *Ashtabula* 868
Warden 869
ships, first 858
Halowax, surface resistance, tests 1753
Harmonics, circuit for production 582
definition 1458
effect upon series transformers characteristics 579
star and delta connected transformers 723
third, auto-transformer, analysis 751
effect of reactance 779
causes 727
constant-current effects 730
effect of maximum voltage 1112
elimination in transformers 754
in star connection, cause 750
in three-phase system 725
reduction factor for generator 728
Heaters, convector type, design 842
vs. radiant type 853
deflector design 849
electric, distribution of dissipated heat 842
test on submarine 846
open coil vs. enclosed coil 852
radiant, advantages 854
type vs. convector type 853
type, design 842
resistor, design 843
Heating electric, advantages 667
convection type 841
disadvantages 671
power consumption 843
radiant type 841
staterooms 847
tests, University of Nebraska 851
Navy 659
Standardization Rules 1810
Helium, liquid, temperature 1005
Hevea rubber, preparation 1770
Hidro-Electrica Espanolo Molinar, data on transformer connections, voltage and capacity 765
High-frequency. (See Frequency.)
Hoist, application of electricity on battleships 1602
control 373
equalizer system 373
gun turrets, battleship *Moreno* 1577
high-speed, choice of motor 881
low-speed, choice of motor 883
variable speed induction motor 379
Horn gap arc-over e. m. f. various air densities 1727
Hydroelectric developments, cost 1612
plants. (See Power Plants.)
Illumination, definition 1865
Standardization Rules 1865

Impedance, definition 1873
Inawashiro Hydro. Elec. Pwr. Co., data on transformers connections voltage and capacity 765
Induction apparatus, classification 1804
Institute, Annual Report 1895
Committees, Board of Examiners report 1913
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of Principles for Professional Conduct report 1912
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Transmission, Insulator Specification. 1107
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U. S. National, report 1912
Use of Electricity in Marine Work, report 1909
Mines, report 1909
evolution 817
members, evolution 817
President's address 817
technical committees 824
trend of future evolution 837
Instruments, classification 1805
milliampere current transformer 571
recording, classification 283
International Engineering Congress Institute Committee, report 1712
Insulation resistance, definition 1852
electric machinery Standardization Rules 1836
material, temperature limits 1817
test voltage measurement, Standardization Rules 1831
transformers, stresses 737 738
transmission line, inconsistency 798
weather-proof, deterioration, tests 271

Insulator, line, 13,000-volt standard 1128
55,000-volt, economy in operation 1429
60,000-volt construction 1430
breakdown, definition 1111
cemented-in metal pins, corrosion 1434 1435
depreciation effect on operation 1721
deterioration in service 119
elimination of defective, method 114
experience in operation 1429
Southern Calif. Edison Co. 113
Yadkin River Power Co. 114
failures, causes 1761
relation to location 112
flash-over, definition 1111
grounded vs. ungrounded pins 126
glass, experience 1439
possibilities 1438
high-frequency testing, advantages 1758
inspection method 1765
investigation with milliampere series transformer 584
leakage troubles 125
mechanical stresses 1735
metal disk, design 152
operating experience 1430
pin-type, specification 1013
puncture under oil 1112
rain tests, specification 1112
reliability, factors that affect 1731
service failures 111
spark-over voltage, effect of altitude 1721
test 1723
variation with density 1723
specification 1107
for testing 1107
general 1107
limitations 1120
surface leakage, measurement 1745
suspension, arc-over voltages, various densities 1725
clamps and fittings 116
deflections observed 1024
of disks 137
factor of safety 1743
failure, characteristics 121
experience 1031
high-frequency, testing 1130
mechanical troubles 136
metal disk, design 152
practical operation 131
precautions in erection 136
service failures 111
specifications 1115
testing electric, specification 1110
for porosity 1736
high-frequency, advantages 1129
troubles from cement expansion 1733
probability formula 1738
voltage testing 1737
pin, combination wood and steel 1064
metal, design 1064
Niagara Falls Power Co. 1064
spark-over e. m. f. effect of altitude 1721
temperature limits, Standardization Rules 1816
tension, definition 145
testing impulse circuits 1126

Integraph, use 1683
on speed-time curves 1695
Ionization by impact 590
theory 583
density at surface of conductor 592
effect on d. c. corona 1655
pressure 1656
free, demonstration 995
Iron, allotropic forms 467
charcoal, Swedish, magnetization curves 464
electrolytic, effect of annealing temperature on strength 465
elastic limit 465
hysteresis loss 473
magnetization curves 464
melted in vacuo, magnetic properties 451
permeability maximum 472
resistivity 473
tensile strength 465
electromagnetic properties, investigations 451
magnetization curves 458
permeability effect of annealing temperature 460
Iron-carbon alloy, effect of annealing temperature upon strength 465
elastic limit 465
equilibrium diagram 467
magnetization curves 464
ultimate strength 465
Irrigation, cost of lands 1628
pumping cost 1628
Ivory, surface resistance, tests 1749
Katsura Gawa Denryoku Kabushiki Kaisha, data on transformer connections, voltage and capacity 765
Lamp accessories, definition 1869
definition 1867
mercury vapor quartz, water sterilization 1217
mine, design 387
requirements 386
operation cost 395
portable electric 385
mines operation practice 392
requirements 397
storage battery 387
Lamps, search. (See Search Lamps.)
tungsten, 20-volt, difficulty 1606
ultra-violet light 1240
ray 1225 1240
Lead, batteries. (See Batteries.)
Leakage, surface, definition 1748
Lehigh Coal & Nav. Co., data on transformer connections, voltage and capacity 765
Light, ultra-violet, bactericidal action 1221
chemical reactions 1121
degree of contact with germs 1223
germicidal action, effect of turbidity 1231 1233
lamps. (See Lamps.)
mercury vapor quartz lamps 1233
quantitative measurement 1218
sterilization apparatus 1223
of water 1217
operating data 1240
plants energy consumption 1229
typical 1228
water treatment cost 1234

Lighting, street, constant-current, advantages 268
distribution systems 266
series system reason for 276
system battleship *Moreno* 1567
Lightning arresters, aluminum a.c. 296
cell, present status 293
d. c. characteristics 295
in hot climate 68
outdoor operation 68
power factors, various frequencies 305
charging current disturbances 279
definition 1856
electrolytic, effect of heat 94
illumination 301
on same pole 703
outdoor substations 58
railway circuit 243
telephone circuits on high-tension poles 1045
transmission line practice 1038
vacuum telephone protection 1094
cloud, explanation 536
current, high-frequency, disturbances 303
discharges, investigation 520
unidirectional 541 543
disturbances, transformers, effect of connections 762
dynamic inductive effects 534
frequency 294 537
hazard, hay barns 538 540
metallic buildings 531
non-metallic buildings 531
investigation with oscillograph 522
oscillograms 523
probability of being struck 530
progressive breakdown 526
protective systems, recommendation 534
protection for buildings, investigations 519
investigation 526
of transformers 706
radius of influence of direct stroke 123
rods, conductance 528
efficiency 527
function 529
grounding 528
protection ratio 527
secondary effects, investigation 532
transformers troubles, experience 691
troubles with transformers, records 696
Load characteristics, light and power system 177
traction system 175
connected, definition 1797
curve, Mexican Lt. & Pr. Co. 1079
factor, automatic improvement 888
definition 1796
effect on competition of central station with isolated plant 896
cost of electric production 1159 1161
lumber mills 1363
mine sub-station 449
power plants 194
saw-mill 1333, 1359 1363
inductive, definition 1795
non-inductive, definition 1795
Locomobiles, performance data 1183

Locomotives, electric B. A. & P. dimensions and data 1378
railway description 1377
depreciation 1391 1399
evolution 404
freight, characteristic curves 1377
mine, mine cost of parts 418
design features 416
development 403
dimensions, evolution 413 415
first 403
lubrication 410
repair cost 418
weights. evolution 412
operation, compared with steam 1382
repairs, cost 1392–1399 1400
Standardization Rules 1863
storage battery for mines 425
freight, electric operation compared with steam 1386
maximum weight on drivers, Penn 1396
Union Pacific 1396
mine tractive effort, evolution 413
steam Mallet type, repairs, cost 1400
repairs, cost 1392 1400
operation compared with electric 1382 1386
Logging, carriage, power requirements 1331
lift, power requirements 1330
cost 1317
electric energy 1319
oil fuel 1319
wood fuel 1319
definition 1316
extent of field for electric power 1317
motor equipments 1318
performance 1318
power requirements 1318
railways, electric operation, cost 1323
power consumption 1322
steam, oil fuel, cost, operation 1323
typical profiles 1321
Los Angeles Aqueduct, data on transformer connections, voltage and capacity 765
Losses a. c. commutating machines 1824
bearing friction 1825
brush friction 1826
d. c. commutating machines 1823
electrical machinery, classification 1822
field rheostat, definition 1827
induction machines 1824
no-load 1826
synchronous converters 1825
machines 1824
transformers 1825
windage 1825
Lumen, definition 1866
Lumber industry, use of electricity 1315
kiln, lay-out 1326
mills, load-factor 1363
power-factor 1363
refuse, fuel value 1353
uses 1356
Lux, definition 1866
Machinery, electric, classification 1800
dielectric strength tests, Standardization Rules 1828

Machinery, electric (*continued*)
efficiency, Standardization Rules 1821
insulation, electric, Standardization Rules 1836
rotating, classification 1800
standards 1807
temperature limitations 1810
limits, Standardization Rules ... 1818

Magnets, plunger. (See Solenoids.)
Magnetizing force, formula 456
Mahogany, paraffined, surface resistance, test 1752
Marble paraffined surface resistance 1752
Maximum demand, definition 1796
Maxwell's equation for solenoids 478
Measurements, current transformer 571
Megger, insulation testing, advantages 1760
Mexican Lt. & Pwr. Co., data on transformer connections, voltage and capacity 765
tower design 1082
transmission report 1015
load curve 1079

Mexican Northern Pwr. Co., data on transformer connections, voltage and capacity 765
Milling, operations, definition 1324
power requirements 1324
Mines, coal, uses for motor 368
electric, locomotive, development 403
hoists, control 373
lamps, requirements 386
locomotive controllers 372
design features 415
evolution 404 415
dimensions 413
lubrication 410
repair costs 418
storage battery 425
tractive effort, evolution 413
weight, evolution 412
portable electric lamps 385
pump motor control 371
ventilation, fan motor control 369

Mississippi River Pwr. Co., data on transformer connection, voltage and capacity 765
transmission report 1014
Motors a. c. induction, concatenated, rolling mill drive 899
wiring diagram 916
drop, definition 1796
wound rotor, specification for dredging ... 1412
d. c. series, braking action 879
characteristic curves 874
for coal and ore bridges 873
series for ore bridge car 874
definition 1800
railway capacity determination. (Also see speed-time curves.) 1713
characteristics Standardization Rules 1862
losses, segregation 1715
rating 1714
Standardization Rules 1860 1880
speed calculation 1802
starting curves, construction 1697
equation 1696
used in coal mines 368

Motor-generator, definition 1800
induction starting conditions 433
synchronous, starting conditions 433
vs. synchronous converters 431
for mine service 445
Multi-recorder 283
applications 290
Name plate, Standardization Rules 1844
Navy, Russian, early uses of electricity 649
U. S. early uses of electric power for steering 624
electric cooking, practice 659
heating, practice 659
gyroscope compass 860
Needle-gap, calibration curves 924
voltages 1832
Niagara Lockport & Ontario Pwr. Co., pole design 1057
tower design 1060
transmission report 1016
Northern Pacific Telegraph system description 325
Oil, crude, cost 1181
fuel for cooking 672
transformer, artificial heating 68
freezing temperature 67
Ontario Hydro. Elec. Commission, data on transformers connections, voltage and capacity 765
Ore bridge hoist, power requirements 880
hoisting speed 880
power requirements 873
rack motor, controller 879
power requirements 877
trolley, power requirements 874
Oscillations, forced, definition 139
transmission lines 128
Fessenden submarine signalling 1555
Oscillograph, cost 1481
in lightning investigation 522
vibrator construction 576
Output, electrical machines, definition 1807
Ovens, electric, power consumption 663 669
Ozone sterilization apparatus, cost 1237
vs. ultra-violet 1235
troubles 1241
water sterilization 1235
cost 1237
Pacific Gas & Elec. Co., data on transformer connections, voltage and capacity 765
transmission report 1015
Pacific Light & Pwr. Co., data on transformer connections, voltage and capacity 765
Paraffine, surface resistance, tests 1753
Parallelism, definition 1446
Peak factor, definition 1794
energy, definition 168
taking device 881
Pearlite, definition 467
Peek's law, explanation of discontinuity 1000
Pennsylvania Water & Power Co., data on transformer connections voltage and capacity 765
grounded star, experience 778
tower design 1059
transmission report 1015
transmission system, connection diagram 1077

Period, definition 1793
Permeameter, magnetizing force, formula 456
connection 455
construction 454
Piping, cost 204
Phase, definition 1794
difference, definition 1794
modifier, definition 1801
Photometry, Standardization Rules 1865
terms, definitions 1868
Planing mill, lay-out 1336
lumber, power requirement 1335
operation, classification 1325
Plant, factor, definition 1796
Plate glass, surface resistance 1750
Pole tops construction, Western States Gas & Electric Co. 1061
design, 50,000 volt circuit 1083
Mt. Whitney Pwr. & Electric Co. 1062
San. Joaquin Lt. & Pwr. Corp. 1056
Washington Water Power Co. 1062
Western States Gas & Electric Co. 1063
square turn, design 1062
A-frame, Niagara Lockport & Ontario Pwr. Co. 1057
steel, design, Southern Sierras Power Co. 1081
life, practice 1047
preservation, treatment, cost 1046
Polyphase, definition 1796
Porcelain, aging, experience 1436
deterioration 142, 148 149
in service 119
molecular fatigue 119, 142, 148 149
surface resistance, tests 1751
Portland Ry. Lt. & Pwr. Co., transmission report 1016
Potomac River, deficiency curves 167
duration curves 167
Power circuit, definition 1446
consumption, battleship auxiliaries 1574
broilers electric 663
cooking, electric, top surface 669
electric heating 843
elevator dredges bucket chain 1411
log carriage 1331
logging railways 1322
ovens, electric 663 669
stoves, electric 663
definition 1795
factor effect on rates 359
definition 1795
requirements, battleships 1574
lumber industry 1315
man type, coal bridge 873
rolling mills 902
plant buildings, cost 204
busbar arrangements 26
generator connections 26
hydroelectric, cost 180
deficiency, stream flow, calculation 164
depreciation 183
effect of basis of development upon cost 166
energy deficiency, determination 172
fixed charges 183
flow data 157
insurance and taxes 183

Power plant, hydroelectric (*continued*)
load characteristics, definitions..... 168
effect on development..... 168
proportion of fixed to variable cost..... 181
steam auxiliary..... 155
determination..... 164
reserve, cost..... 191
investment cost..... 196
over-all efficiency..... 194
production cost..... 196
protection vs. regulation..... 34
steam, cost of operation, calculation..... 184
depreciation..... 183
fixed charges..... 183
insurance and taxes..... 183
Pressure, barometric standard..... 1808
Prime movers, analytical study..... 1123
cost of operation with load factor.....1159 1161
economics..... 1158
investment and fuel costs..... 1158
items of comparison..... 1134
operation cost various load factors..... 1178
present status..... 1133
pulsation, definition..... 1798
variation..... 1797
Protection devices, practice on transmission lines..... 1038
line transformers..... 695
power plants from short circuits..... 23
relays. (See Relays.)
transformers..... 706
vs. regulation in power plants..... 34
Puget Sound Traction Lt. & Pwr. Co., transmission report..... 1016
Quarter-phase, definition..... 1796
Quartz, surface resistance tests..... 1750
tubes for ultra-violet light..... 1240
life..... 1240
Radio, communication, Standardization Rules..... 1876
terms, definition..... 1876
Railroads, electric interurban, a. c. distribution..... 261
electrified a. c. distribution..... 261
distribution.....259 260
operation cost compared with steam..... 1392
telegraph, advantages..... 326
disadvantages..... 326
plant cost..... 323
systems..... 320
typical system..... 321
telephone, advantages..... 332
disadvantages..... 335
plans..... 328
plant..... 330
system..... 321
Railways, electric, advantages of purchasing energy..... 1375
Butte Anaconda & Pacific operation..... 1369
definition of terms..... 1858
distribution, bibliography..... 215
distribution, working conductor, Standardization Rules..... 1858
elevated, distribution system..... 251
interurban, distribution..... 259
operation, compared with steam..... 1382
Standardization Rules..... 1858

Railways, electric (*continued*)
underground distribution system 252
logging, power requirements 1322
typical profiles 1321
steam, operation cost compared with electric 1382 1392
Rankine cycle, efficiency, steam turbines 1138
Rates, electric energy, Minidoka project 1613
Reclamation service 1615
keeping down peaks 887
effect of consumers apparatus on service charges 239
Rating, classification 1809
continuous, definition 1809
electric locomotives, Standardization Rules 1863
electrical machines 1807
equivalent, test 1809
railway motors, Standardization Rules 1860
short-time, definition 1809
units, standard 1808

Reactance, coils. (See Reactors.)
effect on short circuit currents, formulas 44
generators 24
in exciter circuit 50
iron core objections 1540
Reactive factor, definition 1795
volt-amperes, definition 1795

Reactor, busbar, advantages 32
effect in reducing short-circuits 29, 30 31
classification of uses in protecting power plants 24
definition 1798 1805
effect on short-circuit currents, formulas 44

Reactors, feeder, analysis of effects 1510
effect on parallel operation 1516
short circuits 1511
necessity 1510
for protection of power plants 23
generator, leads 27
effect in reducing short circuits 28
protection, comments 46
in converter leads 1524
exciter circuit, tests 50
feeders 41
tie lines between stations 25
insulated windings 1536
insulation of conductor 1539
iron core objections 1540
methods of use in protection, comparative table 40
protective, best arrangement 52
converter leads, tests 1543
definition 1856
feeder, early use 1535
for converter 1531
feeders circuits 1509
in buses 54
practice 1049
railway substations 1527
requirements 47
Standardization Rules 1856
use in power station 48
without iron core 1546
sectionalizing 25
used with synchronous converters 1521
counter m .m. f. coil 1546

Reclamation service, Boise project 1620
development methods 1610
electrical features 1609
hydroelectric development, costs 1618
table 1617
market for electric energy 1610
Minidoka project 1620
power plants operated, table 1611
Salt River project 1619
steam plant development 1623
Williston pumping plant 1623
Resistance, surface, definition 1748
various materials. (See name of Material.)
Recorders automatic 283
Recording instruments. (See name of Instrument.)
Recorders automatic use in central station operation 288
Reflection coefficient, definition 1867
Regulation, automatic, transmission lines 1284
converters, synchronous 361
definition 1836
tests, Standardization Rules 1838
voltage, automatic a. c., system 1285
classification 1805
vs. protection in power plants 34
Relays, over-load, practice in use 1026
reverse-power, tests 270
use 1097
Resistance, at absolute zero test 1004
definition 1746
Resistors, definition 1798 1856
for mine locomotives 411
open coil vs. enclosed coil 852
units, design 843
Rheostats, liquid for mine service 377
Right-of-way, easement vs. ownership 141
obtaining 105
Rio Janeiró Tramway Lt. & Pwr. Co., data on transformer connections, voltage and capacity 765
Rivers, flow data 157
stream flow, deficiency calculation 164
Rolling mill, concatenated induction motor drive 899
concatenation of motors 913
steam, tests 901
Rubber, analysis specifications 1774
composition 1770
compound analysis 1774
30% Hevea, specification 1784
crude, sources 1770
grinder, specifications 1775
Hevea 30% specification 1767
insulating compound, specification 1767
surface resistance, test 1748
trees, description 1770
Sag-tension, curves, copper, wire 1053
Solenoid, design 477
San Joaquin Light & Power Corp., transmission report 1016
Sao Paulo Elec. Co., data on transformer connection, voltage and capacity 765
Saturation factor, definition 1797
Saw mill, edger, lay-out 1337
power requirements 1335
first electric drive in Oregon 1356
gang-saw, power requirements 1340

Saw mill (*continued*)
general lay-out 1329
head saw, power requirements 1333 1334
lay-out 1342
load-factor 1359 1363
power-factor 1363
power requirements 1327
refuse burners, ... 1334
life 1344
exhaust system 1332
fuel value 1353
uses 1366
re-saw, power requirements 1339
rock saw, power requirements 1332
steam equipment, cost 1365
trimmer, power requirements 1338
wiring cost 1364
Search lamps, connections 1572
operating methods 1593
mirror efficiency 1604
Shawinigan Wtr. & Pwr. Co., data on transformer connections, voltage and capacity 765
Shingle, mill, lay-out 1351
Ship, steering by electricity 619
gear electric power tests 640
power calculation 634
Short-circuit currents, maximum 49
through reactance, formula 44
forces 1537
Sierra-San Francisco Power Co., data on transformer connections, voltage and capacity 765
grounded star experience 779
Signal equipment, battleship *Moreno* 1580
Signaling, submarine bell 1552
description 1549
Fessenden oscillator 1555
tests, Fessenden oscillator 1558
use of Fessenden oscillator 1558
Single-phase, definition 1795
Six-phase, definition 1796
Slate, surface, resistance, tests 1752
Sleet, amount allowed for 108
Slide rule for train performance calculation 1707
Solenoids, design constant, table 487 489
formula 514
energy curves 507
inductive exact formula 510
leakage pull 504
magnetic field exact formula 510
maxwell equation pull 478
plunger, total pull equation 505
pull for saturated circuit 493
structural pull 504
with plungers 480
design formulas 482
pull formulas 482
Thompson formula 482
Sound transmission in water, advantages 1551
Southern California Edison Co., data on transformer connections, voltage and capacity 765
transmission line, experience, report 113
Southern Power Co., data on transformer connections, voltage and capacity 765

Southern Sierras Pwr. Co., data on transformer connections, voltage and capacity 765
pole design 1081
transmission report 1015
Specifications, various apparatus. (See name of apparatus.)
material. (See name of material.)
Speed pulsation, definition 1798
time, curves, Castiglioni method 1704 1710
comments 1716
graphic method 1673
Mailloux method 1679
compared with Woodruff 1680
method of cutting proper portions 1705
slide rule 1710
variation, definition 1797
Sphere-gap air density, correction factors 1835
tests 934
breakdown, e. m. f. calculation 925
calibration curves 925
effect of corona on breakdown e. m. f. 989
for e. m. f. measurement 923
gradient, effect of air density 931
temperature 931
high-frequency discharge voltages 1143
precautions against oscillations 945
in measuring high e. m. f. 948
Standardization Rules 1833
spark-over, e .m. f., effect of frequency 943
voltages 1834
surface gradient, formula 925
table, various altitudes 932
Spherometer, specifications 1833
Standardization Rules, bibliography 1883
committees 1787
definition 1793
history 1787
Steel, silicon, magnetization curve 464
transformer, magnetization curve 464
Steering gear, electric, advantages 623
battleship *Texas* 630
electrical equipment, battleship *Moreno* 1575
history 623
Pfatischer, test 651
power calculations 634
requirements 652
tests 640
ships, control 1594
steam, for ships 620
disadvantages 622
Stokers, cost 204
Storage Batteries. (See Batteries.)
Storm prediction by wireless 521
Stott-Gorsuch method of energy, cost, calculation 194
Stoves, electric, power consumption 663
Strand, definition 1846
Submarine signaling. (See Signaling.)
Substations, a. c. 227
arrangement of high-tension buses 82
bibliography 217
buildings, general design 79
outdoor and indoor, cost 80
classification 71

Substation, connection diagram, Penn. Water & Power Co. 1078
d. c., distribution 219
wiring diagram 220
double-bus switchboard, arrangement 85
efficiency 358
fed from distribution system, general design 72
high-tension, general design 77
outdoor vs. indoor 78
in Pennsylvania 71
indoor, in transmission system 75
vs. outdoor 57–75 87
location, choice 78
mine construction and operation 439
load-factor 448
location 441
motor generator vs. synchronous converters 431
operation organization 444
outdoor, classification by load 60
design, considerations 101
details 97
field in South 100
of usefulness 92
fire risk 94
in New England 65
Pennsylvania 71
Middle West 89
large capacity 61
objections 95
saving in building cost 66
small capacity 60
installations 92
supported on tower 90
vs. indoor 57–75 87
why not used in Ontario 98
railway, 241
definition 1858
load curves 1376
protection from short-circuit 1527 1528
rating of machinery 1858
use of protective reactors 1527
specification 359
transformer, arrangement of apparatus 83
wiring diagrams 86
underground, attendance 443
ventilation 442
high-frequency disturbance 303
Surge impedance, definition 139
transmission lines, produced by switching 560 568
sample examples 545
Susquehanna River, deficiency curves 163
duration curves 162
flow data 157
hydrographs 159
Switch, air-break, transient disturbances 1505
automatic quick closing 278
sectionalizing, definition 276
board automatic telephone traffic studies 309
composition material 1596
definition 1854
oil vs. air-break 1505
Standardization Rules 1854
steel construction 1593

Switches, air-break, effect on inductive interference 1495
experience on high tension 1500
opening, oscillogram 1494
vs. oil 1493
automatic recorder 289
air-break vs. oil 1505
for mine service 376
oil, explosion-proof 381
test 379
failures, experience 1031
for outdoor operation 94
freezing temperature 67
maximum capacity 273
vs. air-break 1493
use on transmission line 126
outdoor substations 59
power plant equipment, cost 204
Switching, e. m. f. rise, equation 139
transmission lines, effects 127
Symbols, list 1798
photometric, definition 1871
Synchroscope, definition 1806
Tata Hydroelectric Co., data on transformer connections, voltage and capacity 765
Telegraph compared with telephone for steam railroad operation 319
equipment, battleship *Moreno* 1583
high-speed printing, Kinsley system 1243
line construction, cost 341
characteristics, Standardization Rules 1873
disturbance, effect of transformer connections 786
electromagnetic and electrostatic relative effect 789
interference by high-tension transmission 117
causes 1444
rules for prevention 1445
Morse, evolution 1258
operator capacity 347 350
printing, Baudot, speed 1244
Hughes, early experience 1255
Kinsley, description of operation 1245
operation 1260
Murray, first used in America 1244
speed 1244
Rowland, speed 1244
Siemens-Halske, first used 1244
speed 1245
Underhill 1254
railroad, advantages 326
cost of relaying messages 325
disadvantages 326
plant, cost 323
system 320
speed compared with telephone 348
Standardization Rules 1872
submarine, description 1549
transmission equation 1251
vs. telephone for railroads 337 339
wireless, equipment battleship *Moreno* 1586
Standardization Rules 1876
terms, definition 1876
writing, Pollak-Virag, first used 1245
speed 1245

Telephone, circuit, definition 1446
compared with telegraph for steam railroad operation 319
line characteristics, Standardization Rules 1873
construction costs 322, 329 341
disturbances, effect of grounded neutral 771
transformer connections 786
electromagnetic and electro static relative effect 789
inductive disturbances report to R. R. Commission California 1441
interference, list of reports of joint committee 1482
power company view-point 1490
interference by high-tension transmission 117
lines, interference, causes 1444
conditions permitting parallelism 1447
effect of air-break switching 1495
transpositions 1474
residual e. m. f. and current, discussion 1461
rules for prevention 1445
transformer connections 1449
transpositions 1448
voltage limitation 1496
loading, Standardization Rules 1874
on transmission lines difficulties 1091
factors considered 1088
systems, practice 1041
protection with vacuum lightning arrester 1094
trunk efficiency 309
portable cost 331
railroad advantages 332
disadvantages 335
plant 328
cost 330
systems 320
typical system 321
speed, compared with telegraph 348
Standardization Rules 1872
submarine, description 1549
for sounding 1559
steering torpedos 1559
on *Miami* 1560
toll plant, revenue, factors 1271
traffic study 1063
traffic automatic recorder 310
definition 309
distribution of trunks 316
holding time 315
observations 309
pick load definition 313
studies 309
study 1253
of delays 1268
trunk efficiency 312
grouping 315
vs. telegraph for railroads 339
voice currents, frequency 1459
wireless Standardization Rules 1876
terms, definition 1876
Temperature, ambient, measurement 1811
limitations, Standardization Rules 1861
limits, Standardization Rules 1816

Temperature (*continued*)
measurement, resistance method 1814
Standardization Rules 1813
thermometer method 1814
rise, synchronous converters 361
standard 1808
Standardization Rules 1810
Tennessee Pwr. Co., data on transformer connections, voltage and capacity 765
Tensile strength various materials. (See name of Material.)
Tension insulator, definition 145
Tetrachlornaphthalene, surface resistance tests 1753
Thermometers, Standardization Rules 1812
Third rail, distribution 253
Standardization Rules 1859
Three-phase, definition 1795
Toronto Power Co., data on transformer connections, voltage and capacity 765
tower design 1058
transmission report 1016
Torpedo, steering gear 860
Towers, anchor, present practise 1022
structural steel, cost 80
transmission, bill of materials 1054
design, Appalachian Power Co 1058
assumptions 1292
Great Western Power Co 1055
Niagara, Lockport & Ontario Pwr. Co 1060
Penn. Water & Power Co 1059
Toronto Power Co 1058
Yadkin River Power Co 1053
deterioration, experience 1023
erection method 108
factor of safety 137 143
practise 1024
foundations 107
design 1070
galvanizing, life 109
painting 109
selection 106
specifications 107 1019
Tractive effort, definition 1864
slide rule 1711
Train despatching by telephone 332
resistance formula 1674
Transformers, advantage grounded neutral 769
auto, definition 1805
economic advantages 718
insulation stresses 746
neutral grounding 749
on high-tension line 718
system 745
third harmonic, analysis 751
effect of reactance 779
burnouts records 693
bank, effect of difference in characteristics 736
cases, specification 688
connection boards, specification 690
choice 760
effect on disturbance of telephone lines 786
operation 735

Transformers, connection (*continued*)
experience Au Sable Electric Co..... 777
Colo. Power Co..... 777
Penn. Water & Pwr. Co..... 778
Sierra & San Francisco Pwr. Co..... 778
Yadkin River Pwr. Co..... 778
Italian practice..... 773
leading transmission companies, table... 765
practice Great Western Pwr. Co..... 776
Standardization Rules..... 1842
study..... 753
to minimize interference..... 1449
classification..... 1804
cooling water, waste reduction..... 1309
current. (See Transformer Series.)
cut-out, specifications..... 689
definition..... 1804
drop definition..... 1796
delta connections advantage..... 724
delta-delta compared with delta-star grounded as to inductive disturbances..... 787
connection, third harmonic, cause..... 756
delta-star connection merits..... 757
design, improvements..... 699
efficiency.....
exciting current distortion..... 729
star-connected generator..... 1274
wave form..... 1274
delta connected generator..... 1277
effect of connections..... 1273
fuse protection..... 702
harmonic, third distortion, cause..... 1211
instrument, definition..... 1857
Standardization Rules..... 1857
insulation stresses.....737 738
isolated delta, advantages..... 774
systems line grounds..... 739
lightning disturbances effect of connections..... 762
troubles record..... 696
line, connection boards..... 709
design comments..... 700
experiences..... 685
installed with lightning arresters..... 709
on same pole with lightning arresters..... 703
production..... 695
lightning protection..... 706
specifications..... 692
location in substations..... 74
losses, cost.....694 695
determination..... 1828
name plate specifications..... 688
neutral, grounded, effect of ground..... 741
oil, artificial heating..... 68
cooled, effect of sunshine..... 93
for outdoor use..... 93
freezing temperature..... 67
outdoor operation, practice..... 1047
operation, cost.....694 695
oscillation frequency, measurement..... 1125
outdoor substations..... 58
polyphase, third harmonic, troubles..... 754

Transformers (*continued*)
potential (See Transformer, shunt.)
protection 695
reliability requirements 708
repairs, cost 694 695
selection for distribution, service 224
series, calibration methods 578
flux density 577
milliampere 571
applications 582
specifications 573
reactance determination method 577
vector diagram 575
shunt, wave distortion 1214
single-phase connections, Standardization Rules 1842
star connections, third harmonic, cause 750
and delta connected, effect of harmonics 723
connection, investigation 711
merits 757
regulating effect 759
star-star connection, advantage 755
substation, specification 363
temperature tests, method of loading 1819
three-phase, connections, Standardization Rules 1843
transient equations 560
water-cooled, for outdoor use 93
testing, Standardization Rules 1811
Transmission, d. c., economic radius 14
lines, 12,000-volt, operation 1300
25,000-volt, specification 1084
60,000-volt, protection by circuit connections 1281
150,000-volt, causes of short-circuits 1287
zero regulation system 1284
advantages grounded neutral 769
bibliography 1101
calculation, data required 1085
conductors (See Conductors.)
choice 109
constant-potential regulation system 1284
construction, early experience 1295
delta-delta compared with delta-star grounded as to inductive disturbances 787
entries, design 1073 1076
experience, high altitudes 1297
high-tension problems 105
history in the West 124
inductive interference, list of reports of joint committee 1482
insulation, importance 795
inconsistencies 796
insulators. (See Insulators.)
interference with telephone and telegraph 117
isolated delta, advantages 774
system, line ground 739
Italian practice 773
lightning protection, factors considered 1087
long-span deflections 1024
factors of safety 1024
present practise 1020
mechanical stresses 131
method of connection classification of plants in the world 775
guarding against sag in one span 144

Transmission lines (*continued*)
neutral, grounded at receiving end..... 744
effect of grounds..... 741
operation, causes of short circuits 1287
effect of transformer connections... 735
factors considered..... 1086
one side grounded..... 1029
practice Europe..... 1096
problems in the West..... 124
radius of influence of direct lightning stroke... 123
railroad crossing, design..... 1066
reduction of wind deflections, method..... 133
right-of-way, method of obtaining..... 105
wire crossing..... 1067
sag table, practical use..... 138
sleet troubles..... 134
star and delta connections..... 711
connected, advantages..... 715
disadvantages..... 716
steel-cored aluminum, experiment..... 142
studies..... 753
surges produced by switching.....558 560
sample examples..... 546
swinging, experience..... 1032
switching, effects..... 127
station, lay-out..... 1080
telephone circuits, factors considered..... 1088
disturbances..... 1091
towers (See Towers.)
selection..... 106
transient phenomena, effect of losses..... 566
transposition..... 1079
troubles from insulators..... 131
location, practice..... 1029
wind pressure and deflections..... 132
zero regulation, description..... 1284
practice, Europe..... 1100
railway, star and delta connections, choice..... 807
systems, 60,000-volt..... 1016
85,000-volt..... 1015
100,000-volt..... 1014
150,000-volts, operation..... 1283
bibliography..... 1101
Big Creek, operating experience..... 1287
voltage regulations..... 1284
capacity table..... 765
circuit diagram, Mexican Lt. & Pwr. Co.. 1078
connection diagram, Penn. Wtr. & Pwr. Co 1077
leading companies table..... 765
cutting out load, practice..... 1025
date of opening, table..... 765
delta-delta compared with delta-star grounded as to inductive disturbance.... 787
Italian practice in connections..... 773
opening short-circuit, practice..... 1025
operating voltage..... 765
operation, advantages grounded neutral... 770
effect of transformer connections 735
engineering data, committee report..... 1013
factors considered..... 1086
Pacific Light & Power Corporation operation..... 1283

Transmission systems (*continued*)
railway, definition 1858
switching practice 1025
tests with various connections 712
towers, design, Mexican Lt. & Pwr. Co. 1082
Transpositions, effect in reducing inductions 1474
effectiveness 1480
definition 1447
systems, characteristics 1476
new types 1478
Traveling wave, definition 139
Trolley construction, Standardization Rules 1859
line construction 244
mine locomotives 411
pantagraph, current capacity 1397
life 1387
roller, current capacity 1388
life 1394
Turbines, steam, 1500-kw. steam consumption 20
capacity limitation 1134
cost 1178–1180 1181
different sizes 1141 1142
efficiency limitations 1134
for absorption of peaks 889
operation cost 1178
overload capacity 1168
Rankine cycle efficiency 1138
water rate, different sizes 1136
weight, different sizes 1139
water, compared with other prime movers 1155
economics 1163
efficiency 1155
Francis, efficiency 1157
output equation 1155
vertical, efficiency 1157
Turbo-generators, cost 204
Two-phase, definition 1796
Ultra-violet light sterilization of water 1217
vs. ozone 1235
Underground construction, bibliography 216
Units, photometric definition 1870
Utah Pwr. & Light Co., data on transformer connections, voltage and capacity 765
Vectors, active, definition 1794
definition 1794
Ventilation, electric machines, classification 1803
substation underground 432
Vessels. (See Ships.)
Victoria Falls &Transvaal Power Co., data on transformer connections, voltage and capacity 765
Voltmeter, crest voltage, definition 1805
definition 1805
for peak values 1205
Kelvin electrostatic, use 1635
recording, definition 1805
simplex vibrating 1205
Washington Water Power Co., transmission report 1016
Water sterilization, mercury vapor quartz lamps 1233
ultra-violet, cost 1234
wheels, efficiency 10
Watthour-meter, definition 1806
Wattmeter, definition 1805

Wave, distribution voltage, test 1199
equivalent sine 1794
form, definition 1793
Standardization Rules 1821
harmonic, causes 1460
definition 1458
motion analytical solution 546
rectangular, reflection 549
relation between current and voltage 547
resistance, definition 363
ribbon, analysis 548
reflection 552
sterilizing apparatus for ultra-violet light 1223
telegraph transmission, equation 1251
traveling, definition 139
triple harmonic, causes 1278
Western States Gas & El. Co., transmission report 1016
Welding electric in locomotive repairs 406
Wind deflection for different sizes copper and aluminum conductors 132
in long spans, reduction, method 133
load, amount allowed for 108
Wires, capacitance, Standardization Rules 1853
definition 1846
electric, surface stress formula 1632
electrical tests, Standardization Rules 1850
insulation resistance, Standardization Rrules 1852
Standardization Rules 1846
stranded, definition 1846
Wood, fuel, cost in logging camp 1320
preservation, cost 1046
practice 1046
Yadkin River Power Co., data on transformer connections, voltage and capacity 765
tower design 1053
transmission line experience 114
report 1015

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SOURCES OF DIRECT CURRENT FOR ELECTROCHEMICAL PROCESSES

BY F. D. NEWBURY

ABSTRACT OF PAPER

The problem involved in producing direct current for electrochemical processes is outlined, and the difficulties are pointed out.

Of the methods of power supply using steam turbines that are available, it is shown that:

(a) Direct-connected d-c. turbo-generators are available only in relatively small units, and cannot be designed as conservatively from the commutation standpoint as is desirable.

(d) Unipolar generators driven by turbines have proved unsatisfactory on account of current collection difficulties.

(c) The standard medium-speed d-c. generator connected to a high-speed turbine through gearing affords a satisfactory unit.

(d) The combined a-c. turbo-generator and converter unit probably affords the best all-around method. It is economical, reliable and flexible. Its particular fields of application are where large units and long transmissions are required.

In waterpower plants, direct-connected d-c. generators and a-c. generators with converters are available. The combined a-c.-d-c. equipment is usually the most reliable and economical.

With reciprocating engine units, there is no reason for considering other methods than the direct-connected slow-speed generator.

THE ELECTRICAL power problem involved in all commercially important electrochemical processes is the production of very large amounts of direct-current energy at comparatively low voltages. Single circuits often require as much as 10,000 amperes, and in electrolytic processes the voltage is rarely more than 250 volts. The present paper will briefly outline the problem, list the various methods of obtaining the required electrical energy and compare these methods from the standpoints of efficiency, first cost and reliability in operation.

The electrical problem is intimately connected with the available prime movers and their advantageous operating speeds. In modern installations, steam turbines and waterwheels with their relatively high speeds are of major importance. Reciprocating steam engines are of importance mainly in combination with low-pressure turbines. Up to the present time, gas and oil engines have had little or no application in modern electrochemical plants, but the present rapid development of

the Diesel engine abroad may make its influence felt in the near future.

The design of direct-current machinery, either generators or synchronous converters, of sufficient current capacity for electrochemical work, is a problem of considerable inherent difficulty because of the large currents involved, the high speeds of the preferred prime movers, and the continuous full-load service required. In some cases, as in a-c. turbo-generators, the low voltage involved may become a serious limitation in design aside from its association with the large amperage.

The large currents and high speeds are closely associated and may be discussed together as the commutation problem.

The Commutation Problem.

In direct-current generators and synchronous converters the *speed* and the permissible *number of poles* bear a certain relationship, the product of which, in terms of revolutions per second and pairs of poles, is the *frequency*. In synchronous converters this is, of course, a rigid relationship, due to their synchronous operation. In direct-current generators, the frequency is commonly lost sight of, but at the higher outputs and higher speeds under consideration it is practically as important a limitation as in synchronous converters. The *current output* in commutating machines is proportional to the number of parallel circuits in the armature, which in turn is equal to the number of poles. The tendency, therefore, is to increase the number of poles indefinitely as the required current output is increased. But this indefinite increase is limited, to mention only the most important factors, by the number of current-collecting brush arms that can be placed around the commutator and the number of commutator bars that can be placed between brushes without exceeding safe commutator peripheral speeds. If conservative design limits are not to be exceeded, it is necessary to keep the frequency within 60 cycles and desirable to keep it within 50 cycles.

With the maximum number of parallel circuits and poles that can be used, the total current output is then limited by the permissible length of commutator. At the higher commutator speeds required by the frequencies usual with the d-c. generators under consideration, 800 amperes per brush arm is as high as should be considered under the continuous service required by electrochemical processes. Lower values are commonly used in

60-cycle synchronous converters and higher values are permissible in 25-cycle converters, the peripheral speeds being respectively higher and lower. Uniformly higher values can be safely used for the intermittent service commonly experienced in industrial plants and central stations. Higher values can also be used in very low voltage machines using metal instead of carbon brushes.

With these none too conservative limits of 50 cycles and 800 amperes per brush arm, the following maximum current outputs result, for 250-volt direct-current generators, for the range of speeds commonly used:

Prime mover and generator speed	Poles	Frequency	Amperes	Kw. at 250 volts
1,800–1,500	4	60–50	1,600	400
500	12	50	4,800	1,200
400	16	53	6,400	1,600
300	20	50	8,000	2,000
250	24	50	9,600	2,400
200	30	50	12,000	3,000
175	34	50	13,600	3,400
150	40	50	16,000	4,000

Larger outputs than those listed have in some instances been built at certain speeds but only at the expense of reliability in operation. This is particularly true of direct-connected direct-current turbo-generators.

Double-commutator generators if used would double the above ampere and kilowatt limits, but difficulties inherent in parallel operation of the circuits from two commutators connected to the same winding have, after several unfortunate attempts, caused this construction to be abandoned for large machines where conservative practise has been followed.

It is evident from the above discussion that the major difficulties in building generators and synchronous converters for large currents center in the mechanical design of the commutator. The peripheral speed is pushed to the highest limit to obtain room for as many poles as possible; the length of commutator face is made as long as possible to increase the permissible current per circuit to the limit.

Three constructions have been developed and are in more or less general use to meet these severe conditions.

(a) A modification of the ordinary V-ring construction involving an additional auxiliary V-ring at the outer end of the commutator.

(b) A modification of the ordinary V-ring construction involving a shrink midway between the two ends of the commutator bars.

(c) A simple shrink ring construction involving more shrink rings, depending on the length of the commutator.

The so-called three V-ring type retains all the advantages from the repair standpoint of the simpler two V-ring type. The combined V-ring shrink ring type has the disadvantages from a repair standpoint inherent in the simple shrink type. These two types are comparable in their range of application. Such commutators have been built with 20 to 25-in. (50.8 to 63.5-cm.) face and 5500 ft. (1676 m.) per minute peripheral speed. The simple shrink ring type obviously does not permit of easy repair and is limited to comparatively small commutator diameters. It is, however, the strongest construction available for smaller diameter commutators and is necessarily used for direct-connected turbo units.

Improvements in commutator design and construction during the past four or five years have been largely instrumental in improving the operation and extending the permissible output of the generators and synchronous converters under consideration.

A word in regard to the operation of machines having long high-speed commutators is not out of place. Such commutators built up in part, as they are, of more or less compressible insulating material, require a period of "seasoning" and adjustment before they will operate without further change in shape. A certain amount of such seasoning occurs during the manufacture and test of the machine (where testing is possible), but it is very seldom that additional grinding and tightening is not necessary after installation.

The Distribution Problem

Energy in the form of heavy currents at comparatively low voltages as used in electrochemical work is not efficiently portable. It must be used substantially where it is generated. Very heavy busbar structures, expensive both in first cost and in energy loss, are necessary to carry the large current involved, from the generator to the point at which it is used, and for distances more than a few hundred feet the cost becomes prohibitive. For transmission distances of 1000 ft. (304.8 m.) or more, it is usually necessary to consider transmission at a higher voltage. This introduces the alternating-current gen-

erator and synchronous converter combination of power supply. The relative location of power station and the pots or tanks where the current is used has, therefore, an important bearing on the choice of a power system. This will be referred to again in detail in discussing water power installations.

Voltage Variation

Electrochemical plants usually require some means of adjustment of the voltage in order to maintain constant current under the varying circuit conditions incident to operation. With direct-current generators this is readily obtained by simple field current control, a single generator usually supplying a single series of tanks. With synchronous converters, if the required range is not more than 5 per cent, it can also be obtained by adjustment of the field current, assuming sufficient reactance to exist in the alternating-current circuit. If a greater range of voltage variation is required, several methods are available, the one commonly preferred at the present time involving the addition of a small alternating-current generator to the synchronous converter unit, this generator acting as a synchronous booster. In both generators and converters, the performance under the wide range of voltage sometimes required has been greatly improved, in recent designs, by properly proportioned commutating poles.

Continuity of Service

A feature of electrochemical load that has an important bearing on the satisfactory performance of the equipment is the requirement for steady full-load operation for long periods without shutdown. Many commutating machines that will operate with entire satisfaction on a fluctuating railway or lighting load will fail utterly on a continuous load of no greater value than the average load in the former case. The fluctuating load affords periods of light load during which the commutator and brushes can clean and polish themselves and the daily shutdowns permit the correction of incipient troubles. It is for this reason more than any other that serious trouble has been experienced in so many instances with commutating machines in electrochemical plants. For this reason alone, commutating machines intended for operation in such plants should be of the most substantial and of the simplest type and should be designed, particularly from the standpoint of commutation, well within conservative limits.

The general problem having been stated, the various methods of meeting the required conditions will be considered.

Steam Turbine-Driven Units

Four arrangements involving steam turbine prime movers have been more or less successfully operated:

(a) Direct-connected commutator-type direct-current generators.

(b) Direct-connected unipolar-type direct-current generators.

(c) Gear-connected commutator-type direct-current generators.

(d) Direct-connected alternating-current generator with synchronous converter.

(*a*) Direct-connected, direct-current turbo-generators are limited to relatively small current ratings, due to the very high speed necessary if reasonable turbine economy is to be obtained, and for such sizes as can be built, suitable for electrochemical work, conservative design limits must be exceeded. For this reason it is almost impossible to build direct-connected units that will be generally satisfactory under the severe operating conditions inherent in electrochemical works. The efficiency of the direct-current turbo-generator is low due to the high speed and frequency; that of the turbine is low, due to the speed which, while high from the standpoint of the generator, is low from the standpoint of best turbine performance. The trend of development, both in this country and in Europe, where the most work with direct-connected direct-current units has been done, is away from direct-connected units.

(*b*) Since the difficulties in the design of direct-current generators for electrochemical work have been mainly associated with the commutator, a generator from which commutation has been eliminated would seem to offer a way out of all troubles. In the unipolar type, commutation is eliminated by the employment of unipolar flux, that is, flux of one polarity external to the armature. It is only necessary to collect the generated direct current from the two ends of the armature by means of collector rings and brushes as commonly employed in alternating-current generators and synchronous converters. But it has required only two or three attempts with large units to show that, with the increase in current and speed desired, the simple process of current collection becomes a more difficult problem

than commutation at the lower speeds available with alternative methods. The only unipolar generator large enough to be considered for electrochemical power supply now in commercial operation is the 2000-kilowatt, 250-volt, 8000-ampere, 1200-rev. per min. unit described in a paper before this Institute.* This paper also gives in detail the difficulties encountered and overcome before this unit could be operated with reasonable maintenance cost. Due to the low core loss and windage loss of this type, the efficiency is relatively high. The first cost and maintenance cost, however, are also high.

(*c*) With the development, during the past three years, of a satisfactory gear for the transmission of large powers, the direct production of large currents with steam turbine prime movers has been placed on a much more satisfactory footing. This gearing is usually of the double helical type with the pinion mounted in a floating frame so as to equalize the tooth pressures, in spite of the long face necessary. Obviously, with an efficient and satisfactory gear available, the speeds of the turbine and the generator can be selected within fairly wide limits to suit the conflicting requirements of the prime mover and generator. As a matter of fact, generators which have been supplied for connection to turbines through gearing have been of the same speed and design as generators of the same rating driven by induction or synchronous motors in motor-generator sets. For example, such ratings for 250 volts would be 1000 kilowatts at 500 rev. per min., 1500 kilowatts at 360 rev. per min.; 2000 kilowatts at 300 rev. per min., and 3000 kilowatts at 180 rev. per min., which are all within the limiting ratings and speeds previously given. These units may, therefore, be designed as conservatively as similar generators used in motor-generator sets with relatively high efficiency and low cost. Such units have been in service for several years and have amply proved their dependability. Two large units of 3750 kilowatts, the turbine operating at 1800 rev. per min., and the generator at 180 rev. per min., have been supplied for lighting service.

(*d*) Another satisfactory means for obtaining the required direct current is afforded by turbine-driven alternating-current generators to which synchronous converters are electrically connected. The alternating-current generators may be of the usual synchronous type or of the induction type. This method has been used in a number of copper refining plants, and was

* *Development of a Successful Direct-Current 2000-kw. Unipolar Generator*, B. G. Lamme, TRANSACTIONS A. I. E. E., Vol. XXXI, p. 1811.

used in industrial plants generally prior to the development of the geared unit. While it is lower in cost than either the direct-connected or unipolar types of generators and higher in efficiency than the former, it is somewhat inferior to the gear-connected unit, except when the unit becomes so large that 3600 rev. per min. turbines cannot be used in the geared unit. This method possesses obvious advantages in flexibility of plant arrangement. For plants in which the transmission distance is short enough, the generator can be designed for the required converter voltage and the converter connected directly to the generator terminals. Where, however, distances are greater, the generator can be wound for a higher voltage and step-down transformers installed with the converters at the electrolytic tanks.

Synchronous converters have been used instead of motor-generator sets primarily because of their higher efficiency. Considering the most unfavorable conditions from the standpoint of the synchronous converter, that is, a 60-cycle synchronous booster converter with transformers, the efficiency of a 1000-kilowatt, 250-volt, synchronous converter outfit would be at least 92 per cent, while the efficiency of an equivalent motor-generator set without transformers would rarely be higher than 88 per cent. Without transformers, without the boosters (where large variations in voltage are not required) and with a 25-cycle system, the comparison would be still more favorable to the synchronous converter.

If it is necessary to entirely separate, electrically, the different circuits, each consisting of a synchronous converter and series of tanks, this can be done as effectively by the use of transformers in connection with the converters as by the use of separate generators in motor-generator sets.

If transformers are necessary, the combined cost of the converter and transformer will be substantially the same as that of the motor-generator set.

The inherent advantages of the induction type generator for this service have been pointed out in a paper before the Institute,* in which a specific application to electrolytic work was described. The stators of the synchronous and induction generators are substantially the same; the difference between them lies in the rotors. The rotor of the induction generator consists of a simple winding formed of bars short-circuited by end rings as in the more familiar induction motor. As in the

*The Non-Synchronous Generator in Central Station and Other Work, W. L. Waters, TRANSACTIONS A. I. E. E., Vol. XXVII, 1908, p. 157.

motor, this winding need not be insulated from the core, and there are no collector rings and brushes which, at turbine speeds, require some care and attention. While, however, the induction type rotor is inherently simpler than the synchronous generator rotor, so much more development work has been done with the latter type that, as actually constructed, the synchronous rotor is, if anything, more reliable in operation than the rotor of the induction generator. The exciting or magnetizing current of the induction generator must be supplied from the synchronous converter so that the converter is under the handicap of operation at a power factor lower than unity. This handicap may become serious if it is desired to increase the voltage above that originally contemplated. The voltage of the synchronous generator on the other hand is very simply controlled by changes in its exciting current, so that in this respect the combined alternating-current generator-synchronous converter unit is on a par with the direct-current generator. For these reasons the induction generator has not been extensively applied.

The comparative efficiency of the various methods just described, based on a 2000-kilowatt, 250-volt unit, are given in the following table:

Apparatus	Efficiency
(a) Direct-connected commutator type generator, three 750-kilowatt, 1500 rev. per min.	89
(b) Direct-connected unipolar type generator, 2000-kilowatt, 12,000 rev. per min.	92
(c) Gear-connected generator,	
Gear 3,600-300 rev. per min.	98
Generator 2,000 kilowatts, 300 rev. per min.	93.5
Combined	91.6
(d) Alternating-current generator-converter set	
A-c. generator, 2,000 kilowatts, 3,600 rev. per min.	94.5
Cables	99.5
Synchronous converter, 2,000 kilowatts, 360 rev. per min.	96
Combined	90.2

In considering these efficiencies, the lower economies of the lower speed turbines for (*a*) and (*b*), and for (*c*) in larger sizes, should not be lost sight of.

Waterwheel-driven Units

With waterwheel-driven units, the choice lies between direct-connected direct-current generators or direct-connected alternating-current generators and synchronous converters. In very few plants can waterwheel generators be located near enough to the electrochemical plant to justify the installation of direct-connected direct-current generators, in view of the

expensive structure required for the transmission of the heavy currents. The various questions involved in such an installation can best be brought out by a comparison of the d-c. and a-c.-d-c. installations in a specific instance.

For this purpose a plant having an ultimate capacity of 120,000 h.p. with a water power having a 250-ft. (76.2-m.) head has been chosen. The largest direct-current units that could be even considered are 5000-kilowatt, 250-volt, operating at a speed of 170 rev. per min. It will be noted that this current rating in proportion to the speed is higher than previously given as a conservative rating. Nineteen such units would be required and with a diameter of approximately 25 ft. (7.6 m.) these generators would require a power house approximately 700 ft. (213.3 m.) long. Contrasted with the direct-current equipment, eight 12,500-kv-a., 277 rev. per min. 60-cycle generators could be used. These generators could be placed in a power house approximately 250 ft. (76 m.) long. In each case one spare unit is included. In further contrast with the direct-current units, the alternating-current units are well within conservative design limits, much larger generators at higher speeds having been built. With the direct-current units a lower speed has necessarily been chosen than would be most economical for the water wheels, consequently the water wheel efficiencies are lower for the direct-current plant than for the alternating-current plant. The comparative efficiencies with the two systems are shown in the following table:

COMPARATIVE EFFICIENCIES.

	D-C. generation	A-C. generation and converters
Waterwheels	80 per cent	89 per cent
Generators	95	96
Transmission, assuming a distance of 2000 ft. (609 m.)	92	99.5
Step-down transformers		98.6
Synchronous converters		96
Low-tension wiring from step-down transformers to load (assuming 50 ft. 15.2 m.)		99.6
Over-all efficiencies (from water to load)	60.7	80.1

Ten per cent difference in efficiency would mean an appreciable difference in the investment cost and, therefore, in the cost of power, even with a water power installation. In the present instance, assuming an investment cost of $60 per h.p., this difference would amount to three-quarters of a million dollars.

The comparative costs of the two propositions, based on the total cost of the direct-current system as 100 per cent, are shown in the following table:

	D-C. generation	A-C. generation and converters
19 5,000-kilowatt 170-rev. per min. 250-volt d-c. generators with water wheels complete (one unit spare) approx.	60 per cent	
8 12,750-kilowatt 277 rev. per min., 11,000-volt 60-cycle a-c. generators with waterwheels complete (one unit a spare) approx.		38 per cent
Transmission [based on 90,000 kilowatts 250 volts for 2,000 ft. (609 m.) with copper at 10 ¼ ct. per lb. (0.45 kg.) loss 8 per cent] approx.	38	1
19 5250-kilowatt, three-phase, 60-cycle O. I. W. C. transformers 11,000 to 180 volts (one a spare unit) approx.		4½
19 5,000-kilowatts, six-phase, 250-volt d-c. synchronous converters with 10 per cent buck and 10 per cent boost (one a spare unit) approx., (Each unit consisting of two 2500-kilowatt converters)		29
Low-tension wiring from step-down transformers to load [50 ft. (15.2m.) assumed] approx.		1
Switching equipment, approx.	2	7½
Totals	100	81

The above costs do not include the cost of supports, anchors and insulation for the direct-current transmission line which, with the very heavy structure necessary, would be a considerable item.

Obviously with a smaller plant and, particularly, with a shorter transmission distance, the cost of the direct-current plant would be materially less. The efficiency, however, would not be greatly improved unless more efficient wheels could be used, and the drop in the transmission reduced by a material increase in the cost of this part of the plant. For example, for a plant of 60,000 h.p. instead of 120,000 h.p. and assuming 1000 ft. (304.8 m.) length and 5 per cent loss for the direct-current transmission, the a-c.-d-c. plant would still have 8 per cent higher efficiency but its cost would be 10 per cent more than the direct current. Even on this basis the a-c.-d-c. plant would be more economical. Its flexibility is, moreover, an additional advantage of great importance.

These figures are well substantiated by the change in practise

found desirable by one of the largest aluminum companies. All of the recent work done by this company has been with alternating-current generators and synchronous converters. A large installation involving nine 2500-kilowatt, 500-volt, 60-cycle synchronous converters is now being erected and a still larger installation involving 60-cycle machines of similar rating is in process of construction.

At the lower voltages more commonly involved in electrochemical work, a 60-cycle system has considerable advantage over a 25-cycle system. The higher frequency is an advantage from the standpoint of the turbine because of the higher available speeds; costs throughout the installation are less. In the synchronous converters the higher frequency is an advantage due to the larger number of poles and armature circuits for a given speed. At the higher voltages, that is, 500 to 700, sometimes used for the reduction of aluminum, there is a slight advantage, from the standpoint of the synchronous converter design, in the lower frequency. This, however, is not sufficient to overcome the other disadvantages incident to the lower frequency.

Reciprocating Engine Units

While these units have very little application in modern plants, they should be mentioned to complete this survey. From the generator standpoint the lower speeds common with reciprocating units is a decided advantage, permitting as it does a large number of poles and armature circuits. On account of this fact there is no reason for considering other schemes than the simple direct-connected commutator-type direct-current generator. The efficiency of a 2000-kilowatt, 250-volt unit would be 94 per cent.

Conclusion

From the many schemes proposed for the generation of direct current for electrochemical plants, two plans assuming steam turbine prime movers have decided advantages in efficiency and reliability and flexibility in operation. These are the gear-driven commutator-type generator where the distance between the power plant and the place of utilization is short and the combined alternating-current generator and synchronous converter plant when this distance becomes too great for economical low-voltage transmission or the units become too large for economical turbine speeds.

DISCUSSION ON "SOURCES OF POWER FOR ELECTROCHEMICAL PROCESSES" (NEWBURY), NEW YORK, JANUARY 9, 1914.*

G. A. Roush: Mr. Newbury takes up a standard outfit, with a capacity of 120,000 h.p., and draws comparisons on that basis. I think it would have been, possibly, of more value to the people interested in the electrochemical utilization, to have used for examples sizes of installations that are more nearly those that are actually in use, that is, as Mr. Addicks stated in his paper, in the neighborhood of 1000 to 1500 kw.

F. A. Lidbury: In only one line of electrolytic industry—the reduction of aluminum—are single installations of 120,000 h.p. conceivable at the present time; indeed, there is no other single line of electrolytic manufacture, the power requirements of which throughout the United States exceed 100,000 h.p., and the instance of water power generation examined by Mr. Newbury is so far removed from anything approaching what is possible in the refining of copper and the other metals, that his analysis has practically no bearing. Most electrolytic plants of importance, the aluminum industry being excluded, will be found to have a power consumption somewhere between 1000 h.p. and 10,000 h.p., and so far from single units of 5000 kw. being common, any plant which is consuming 5000 kw. will be found to be, even today, a considerable factor in its particular line of manufacture. Even in the largest electrolytic installations (still excepting aluminum plants) the size of units does not often exceed 1000 kw. Most electrochemists would, therefore, have been more interested in comparisons made between installations of units of capacities of this order than in those with which Mr. Newbury specifically dealt in considering water power generation. That the results of such a comparison would have been very different is clear from a consideration of his own data; it will no longer be correct to say that "in very few plants can water-wheel generators be located near enough to the electrochemical plant to justify the installation of direct-current generators." It is obviously true that where transportation or other conditions demand the location of the electrolytic plant at a considerable distance from the power house, d-c. generation will be out of the question in any case, but where no such condition is involved, it will usually be found not only feasible but the only rational scheme.

Having somewhat modified our starting point in regard to the size of unit which should be taken as typifying electrolytic

*At this joint meeting two other papers were presented, "(1) "Limitations of the Problem of Electrolytic Deposition," by Lawrence Addicks, of the American Electrochemical Society, and (2) "The Power Problem in the Electrolytic Disposition of Metals," by H. E. Longwell, of the American Society of Mechanical Engineers. These papers are published by the societies mentioned and not by the A. I. E. E.

requirements, Mr. Newbury's table connecting the prime mover and generator speed with the conservatively practicable capacity of units assumes quite another aspect; it teaches us that d-c. generators of 1000 kw. capacity can be directly connected to waterwheels of speeds as high as 600, if a voltage of 250 is used, and as high as 300 in the extreme case of voltage requirements as low as 125. Obviously, under typical conditions, there ceases to be any difficulty in d-c. generation in connection with any waterwheel speed that is likely to be met with. This, in turn, puts quite a different aspect upon the comparative efficiency of d-c. generation and a-c. generation with converters, as is obvious from the fact that the bulk of the difference in over-all efficiencies from water to load in Mr. Newbury's table is accounted for by the necessity of adopting, under the conditions which he examines, a turbine of lower speed and of 9 per cent lower efficiency for connection to the d-c. generator. Under conditions more truly typical, this necessity vanishes. It will usually be found advisable under these conditions to require no modification of waterwheel speed to accommodate either alternator or d-c. generator, as there will be no difficulty in obtaining either machine to give first-rate performance at the speed most advantageous from the point of view of waterwheel design. As a general rule it will be found much easier to get the electrical manufacturer than the turbine maker to make what compromises are necessary without appreciable loss of efficiency. There will, in any case, be but a slight difference in efficiency of a-c. and d-c. generators, probably not exceeding one per cent, and while there may be a considerable difference in cost between d-c. and a-c. units, the magnitude of this will depend upon a number of conditions, chief of which is the d-c. voltage; under favorable conditions, *e. g.*, where d-c. voltages approaching or exceeding 250 can be used, the cost of a-c. accessories (exciters, switching equipment, etc.) will go far towards completely wiping out this difference. In most cases, therefore, it is practically a question of determining the distance to which the value of the synchronous converter set with transformers and accessories, and including building space and investment in copper, will enable the current to be carried with the same per cent energy loss as that involved in transformation by the synchronous converter set; and perhaps it would be only in accord with experience to carry out this calculation with a healthy skepticism as to whether the over-all efficiency of a-c. generation and converters as expressed by the product of the efficiencies of the component parts of the system under test conditions will not be appreciably reduced under conditions of actual operation. Viewed from this standpoint, the radius of economic transmission of low-tension direct current will often figure out surprisingly large, and will, in almost every instance in which it is not necessary to place the load at a point determined by other considerations,

usually be sufficient to include not only a possible point of delivery to the load, but also the whole of the load-absorbing portion of the plant, within its area.

Economically, at least, two other points are to be considered. It is obvious that direct operating cost (*e.g.* attendance, oil, etc.) will in some respects be practically doubled by the necessity of maintaining two stations containing moving machinery, instead of one; and maintenance charges will also be considerably increased, though possibly not to the same extent. The smaller the installation, the more important this point becomes. Secondly, due weight must be given to the difference in depreciation on the same sum invested, respectively, in copper conductors and in synchronous converter equipment. This difference would be likely to appear more clearly at the end of a number of years' running than in the early stages of the installation. One cannot, of course, prophesy what the scrap price of copper is likely to be in 10 or 15 years time, but one has a pretty good idea of what the scrap price of a synchronous converter equipment of that age is likely to be. Both these factors have to be included in any proper scheme of economy, and they are not by any means insignificant in magnitude.

Lastly, the electrochemical engineer is also apt to have a prejudice in favor of simplicity. What he wants in the way of power equipment is something which will be primarily characterized by smoothness, ease and reliability in operation, and he is apt to know by experience that this is not most likely to be obtained by multiplying the electrical links in his chain of power machinery, or the number of points needing continual attention to insure the best operating results.

I frankly concede that these remarks do not apply to water power installations of such magnitude as Mr. Newbury deals with, and I also concede that he has pointed out that the validity of his conclusions decreases with decrease of unit capacity. It seemed highly desirable, however, that this portion of the subject should be discussed in its bearing upon the vast majority of electrolytic installations.

F. L. Antisell: It seems that one point which has been overlooked is the efficiency of partial loads. The reciprocating engine is capable of having the characteristic of the 100 per cent load, by varying the speed of the engine, tending to uniform mean effective pressure. In the various types of turbines, when we come to running at partial loads, we find a great falling off in efficiency. I do not think this point has been brought out fully, and it is a very important point in connection with this subject.

J. B. F. Herreshoff: Our system at first apparently required small units, and those were supplied with high-speed triple-expansion engines of the torpedo type. They were first installed about 15 years ago, in units of about 400 kw., making 350 rev. per min., operated condensing. Those were after-

wards operated with a low-pressure turbine. The engines gave very satisfactory results, but the cost of maintenance on a great many units is an item that we have to avoid. The first of the turbo-generators that we had was the first one of the Parsons type made in the United States, running about 5000 to 6000 rev. per min., generating direct current, and it had very long commutators. After that we put in an acyclic generator of 2000 kw., but we had trouble with the collectors. We found an enormous amount of heat going away from the machines, and inasmuch as it came out of four or five holes, it was a simple problem to take the temperature of the ingoing and outgoing air. We found that 30 per cent of the energy was going off in heat.

We also felt there must have been some mistake in the method heretofore used in arriving at the efficiency of this machine, which was supposed to run up to ninety-five per cent, but this method of getting at the efficiency seemed to be a pretty good one.

The next problem was how to get the best arrangement for making an alternating current, starting first with the steam turbine. Mr. J. B. Herreshoff conceived the idea of an alternating-current generator of a low voltage, connected without any transformer to a properly designed synchronous converter. A good many of these outfits have been built and they seem to have special advantages for this type of work.

J. B. Herreshoff: In an electrolytic plant, if you double the amperes you will deposit your copper in half the time. This will take double the voltage, and the result would be you would have four times the power in your tanks. There are some advantages in doing this. The temperature of the electrolyte would be kept up, and in some cases it might not be necessary to use steam. This is done at Great Falls. At that plant I believe they use a current density of about 40 amperes per sq. ft. (0.09 sq. m.), and the temperature of the electrolyte there is 150 deg. fahr. In the multiple system, the temperature will vary generally in the East here from 130 to 135 deg. fahr. The cost of keeping the electrolyte warm is so great that the temperature can not very well be kept higher.

It is interesting to note that if we do double the current density, although the power goes up four times, the cost per pound of copper only doubles. The objection to doing this, we have found, is that the deposits are not so smooth; they are apt to be crystalline, more brittle, which is often a very serious matter in the handling of the cathodes.

Mr. Newbury mentioned that it was very easy to vary the voltage, where there was only one synchronous converter connected with one alternator, by varying the field of the alternator. This is true. It can also be varied, to some extent, by varying the length of the synchronous converter, which has the effect of changing the power factor. Where two con-

verters are connected to one alternator, differences of voltage can be obtained by weakening the field of one slightly, and strengthening the field of the other. The advantage of doing this is that you can use a larger turbine and alternator, which, of course, means a little more cost in installation, but it also means a little better economy. The objection to this method of control is that on account of the power factor not being unity, the converter will heat up in some parts of the armature, but not seriously, if the difference of voltage between the converters is not more than thirty or forty.

C. O. Mailloux: The statement which has been made that the character of the copper deposit depends upon the current density requires some qualification. That it is true in cases such as those which have been referred to is due to the peculiar circumstances and conditions of the cases. It is not true as a general proposition, and the wide-spread belief that a regular deposit of ductile copper of good quality can be obtained only with low current-densities is quite erroneous. The quality of the copper deposited at the cathode may be independent of the current-density within very wide limits. It is possible to obtain very good deposits (and also very bad deposits) at any current-density between 10 and 1000 amperes per sq. ft. (0.09 sq. m.). A current-density of 1000 amperes per sq. ft. will doubtless seem enormous to those who are familiar only with the current-densities employed in electrolytic copper refining, which seldom exceed 30 amperes per sq. ft.; but it is true, nevertheless, that copper-deposits of the finest quality can be obtained at that high current-density. In 1885, I was called upon to develop a process of rapid electrotyping. Electrolytic copper "shells" such as used for making ordinary electrotypes have a thickness ranging from 0.010 to 0.015 inch (0.25 to 0.38 mm.). This means a weight ranging between 0.45 and 0.70 lb. per sq. ft., and the quantity of current required to deposit that amount of copper, allowing for some loss in current-efficiency, *i.e.*, allowing for electrolytic action which causes the deposit of something else besides copper—hydrogen, for instance—at the cathode, will range between 200 and 300 ampere-hours per sq. ft. With a current-density of only 10 amperes per sq. ft., the time required will therefore be from 20 to 30 hours. The problem which I was called upon to solve was to shorten the time to not over two hours. It was important that the copper shells should be very uniform in thickness, free from "pin-holes", and of the very best quality of copper. Considering their large size—that of a newspaper page—it seemed difficult to meet these requirements. It proved possible, however, to obtain deposits of the finest quality and uniformity with current-densities as high as 1000 amperes per sq. ft. This enabled the time to be cut down to less than one-half hour for a shell of full thickness; but for the purpose in view a rate of deposit producing a shell in one hour was sufficient and was adopted in practise.

These results were not mere laboratory experiments. The process was in regular operation for many months, turning out several hundred pounds of electrotype shells every day, and the number of shells found defective was surprisingly small. The secret was simple enough; it was merely a question of *keeping the electrolyte under control*, so as to maintain it in substantially the same chemical, electrical and physical condition all the time. The amounts of copper sulphate and free acid in the electrolyte, the density, specific resistance, and temperature of the electrolyte, were all maintained within certain limits; and the electrolyte was systematically agitated and circulated. The object in view was, of course, to put the electrolyte in the best possible condition to meet the urgent demand for "ions" resulting from the high current densities. If there is not enough copper in solution at the cathode to satisfy the "cation" requirements of the current, the deficiency will be made up by a partial deposit of hydrogen with the copper; and it is well known that a very small proportion of hydrogen is sufficient to alter the quality of the deposit. The great difficulty is to prevent the deposit at the cathode of other elements than copper. Hence, as a rule, high current-efficiency is a condition (though, perhaps, not the only condition) for a good deposit.

High current-densities (up to 300 amperes per sq. ft.) have been employed in more recent years in connection with processes for making copper tubes and sheets by the electrolytic deposition of copper on rotating cylindrical cathodes.

In electrolytic copper refining, high current-density, though still possible, in theory, is excluded, in practise, for the good reason that "it would not pay." Aside from the increased amount and cost of electrical energy that would result from the use of higher current-densities, there are other important considerations which argue strongly in favor of low current-densities. The electrolyte is more complex and much more variable in chemical constitution by reason of the impurities contained in the anodes, and which eventually pass into the solution, or else form a part of the "slime." This slime contains the precious metals, gold and sliver, which are recovered through the process of refining. It is necessary to guard carefully against loss of precious metals by their being carried over to and deposited on the cathode, either electrolytically or mechanically. This means, practically, that the electrolyte must not be stirred violently; indeed, it can scarcely be stirred at all, to increase diffusion. The difficulties and the cost of maintaining the electrolyte at a high constant conductivity, either by raising the temperature, or by chemical treatment, and the difficulties incidental to circulation or agitation of the solution, are very much greater than in the case of an electrolyte serving for electro-deposition when using anodes of pure copper. Experience has shown that the advantages, such as increased output from a plant of given size, etc., do not offset the disadvantages and the increased cost.

There is also some misunderstanding in regard to the cost of the power required for depositing copper. Paradoxical as the statement may seem, it is possible, theoretically, to deposit any amount of copper with a given amount of electric power. A mathematical demonstration of this possibility was given by me some twenty-five years ago in a series of articles published in the *Electrical Engineer*. The electrochemical principles on which this interesting possibility depend were set forth by Dr. N. S. Keith, the founder and first secretary of this Institute, in the discussion of a paper on "Depositing Vats in Series," read by Mr. Slater, at the first meeting of the A. I. E. E. at Philadelphia, in October, 1884 (see Volume I of the A. I. E. E. TRANSACTIONS). When there is no polarization-effect produced at the anode or the cathode, in other words, when the thermochemical reaction (heat of formation) incidental to the dissolving of copper at the anode is exactly equal to that incidental to the deposit of copper at the cathode, as is the case when electrolysis takes place with a low current-density between plates of pure copper in an electrolyte of pure copper sulphate, all the "ions" then consisting of copper only, there is no consumption of energy except in overcoming resistance. In such a case it is possible to increase the total amount of copper deposited without increasing the total amount of electrical energy expended. Suppose that, in a given case, starting with a certain number of vats in series, we add a second series, exactly like the first one, in multiple. If the current-density in each series be made one-half what it was in the first series, the total current passing through the two series in multiple will be the same as before, and the total amount of copper deposited, on the assumption of 100 per cent current efficiency, would be the same as before. The difference of potential between the anodes and cathodes in each vat will be reduced to one-half, because it only depends on resistance-drop, in the absence of polarization. If we still wish to retain the same working power in the circuit, we may add as many cells again in series to each of the series. We will then have four times the number of vats and four times the number of cathodes on which copper is being deposited with one-half the current density, and, consequently, one-half the rate of deposit that was obtained when one set of vats alone was in use. With four times the number of plates receiving a deposit at one-half the original rate, the total output in copper will be doubled. By increasing the number of series connected in multiple to four, the number of vats in each series could also be increased to four times the original number. The current density for the same total current and energy would be one-quarter what it was originally, but with sixteen times the number of vats and plates in use, the total amount of copper deposited with the same electric power, would be four times what it was before. It is seen that the number of vats, and, consequently, the size and cost of plant necessary to treat such a large amount of copper, would

increase in geometrical ratio as compared with the increase in output, and it is obvious that such a plan would not be economical. The saving in cost of power which might be effected by reducing the current-density to a very low value in a plant arranged as just mentioned, would come far short of offsetting the additional fixed charges and operating expenses of the greatly enlarged plant necessary, to say nothing of the loss of interest resulting from the greatly increased total amount of copper that would be under treatment at the refinery. Refining copper, being a commercial proposition as well as an electrochemical and mechanical problem, must be carried on under conditions which are compatible with the highest economy and which give the most profit. It is found in practise that the best results are obtained when the current-density ranges between 15 and 50 amperes. The exact current-density corresponding to the best financial result will naturally vary somewhat with the locality, design, and operating conditions of the particular refinery.

Lawrence Addicks: The higher the current density the more rapid must be the circulation in order to keep sufficient copper close to the cathode, which is the secret of good deposits. We are limited in that by the silver and gold losses, as the contents of the anode are left as insoluble slime in the tank, and we cannot afford to stir that up and foul the cathode. That is the commercial point which limits us.

I think a 1500-kw. turbine will use 17 lb. of steam per kw-hr. on the same basis on which I have shown the curves of the reciprocating engine. Take the triple-expansion engine at 15 lb., and we have a difference of 2 lb. of steam per kw-hr., which, at 15 cents per 1000 lb. is $39.42 a year, which is $2.60 per kw. Without disputing 18 per cent, that Mr. Longwell wants for depreciation, interest, etc., that allows us to spend $15 per kw. more on that installation, and right on this question of steam consumption, the reciprocating engine for that size unit certainly holds its own.

Mr. Newbury, on the other hand, says that simplicity is a great point, that the reciprocating engine is a complicated affair, and that we would much better have a steam turbine for the prime mover, an alternating-current generator, a transformer, a synchronous converter, and a booster. I think on that score also the reciprocating engine has something to be said for it.

C. H. Vom Baur: The oil engine has been used only to a slight extent in this country in electrochemical industries. Now that oil can be sold in the harbor of New York for less than three cents a gallon, 2.83 cents, actually in lots of 80,000 gallons, and in view of the high load factor in this work, the subject of the oil engine has again come to our attention. These engines will make power for 0.45 of a cent per kw-hr., taking interest and depreciation at ten per cent, and figuring in all the taxes and insurance, including liability insurance. There is so much of this heavy oil on the market, that contracts are made for a number of years.

These oil engines have been made in Europe in sizes as large as 2000 h.p. to a cylinder, so with the average size plant in which engines are used in this electrochemical industry, and with the average size unit, all the conditions can easily be met with the oil engine and with the oil that is now on the market.

Lawrence Addicks: There seems to be no question that it is possible to do better with the gas engine than the best that could be done in the case of steam. I looked at one of the oil engine installations in this country recently, I think it was of 400 or 500 h.p. capacity. The only difficulty with it was that it was subject to heart failure, and when it had one of these strokes and was shut down, there was considerable difficulty in getting it started. I think this engine is about two years old, and it has not shown the reliability that we feel is necessary in electrolytic work.

H. E. Longwell: As I understand it, the object of the meeting tonight is to consider what is, and what is not, a suitable prime mover for electrolytic plants; and when I say I do not think the gas engine is most desirable for the specified operating conditions, I do not want any one to get the idea that I do not think the gas engine has its uses. Neither do I want you to get the idea that I do not think the low-pressure steam turbine has its legitimate field of usefulness.

I have discussed the several types of power plant solely with reference to the operating conditions as I understand them, and I have endeavored to do it impartially and dispassionately. I also wish to assure you that my advocacy of the complete expansion turbine for this service, is entirely disinterested, and is based only on what in my estimation are sound principles of commercial engineering.

F. D. Newbury: Some criticism has been aimed at what I, in writing the paper, considered the least important part of the paper—the waterwheel-driven plant. The steam-driven plant is, of course, the one in which the copper refiners in the vicinity of New York are mainly interested.

In connection with the criticism of the size of waterwheel plant considered, it was not brought out in the paper as probably it should have been, that waterwheel plants are used mainly in the aluminum industry where large amounts of power are required, and for that reason a large plant was purposely selected. Experience has shown that in such plants the apparently more complicated power plant consisting of two or three links is in reality simpler, more reliable, more efficient, and less costly to maintain, than the installations consisting simply of the waterwheel and generator. With plants of 1000 kw. or 1500 kw. or even 2000 kw., I agree that the alternating-current generator and synchronous converter cannot compete with the direct-connected generator, if the plant can be located near the place of utilization of the current. In such circumstances, the distance of transmission is the only thing that would dictate the use of the alternating current-direct current system.

The possible difference between calculated and actual efficiencies was mentioned. The efficiencies of the various classes of apparatus given in this paper represent actual operating efficiencies, liberal allowance having been made for all losses.

Several of the speakers questioned my consistency in emphasizing the necessity of simplicity and, at the same time, advocating a plant involving the alternating-current generator, synchronous converter, and in some cases transformers and the synchronous booster. This position is entirely consistent and I believe Mr. J. B. Herreshoff will bear me out when I say that with the long experience he has had with most of the types of apparatus discussed, the one piece of apparatus he has had the least trouble with has been the synchronous converter. Obviously an alternating-current generator is more reliable, more efficient, than even a low-speed direct-current generator.

Mr. Herreshoff spoke of the possibility of obtaining to a certain extent voltage regulation with two synchronous converters supplied from one alternating-current generator, by variation in power factor. What he said is perfectly true, but if that method is contemplated, it must be taken into consideration by the machine designer and properly allowed for, because a slight difference in power factor will mean a very considerable increase in local heating, and unless the converter is designed for that condition, it may cause a burn-out near the tap coil.

F. W. Harris (by letter): One very real advantage of the a-c. generator-sychronous converter plant over the d-c. generator plant lies in the fact that interchange of power with other stations is then possible. There is now little or no market for 250-volt d-c. current even in the cities and in the neighborhood of electrolytic plants there is none. The sale of excess d-c. power is therefore not practicable. On the other hand, there is a ready market for excess a-c. current at any standard frequency, and in an emergency, additional power can often be bought. There are certain seasons when power commands a premium and the fact that the power produced is a marketable commodity is an important one.

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PROTECTIVE REACTANCE IN LARGE POWER STATIONS

BY JAMES LYMAN, ALLEN M. ROSSMAN AND LESLIE L. PERRY

ABSTRACT OF PAPER

The concentration of a large generating capacity on the busbars of a single power station demands protection against an excessive flow of current into an accidental fault. Reactance coils can be used in various ways to limit the instantaneous current flow. Reactance coils in the generator leads, while limiting the flow of current from the different generators, are not efficient for limiting the current flow into a fault.

Bus reactances are less bulky and less expensive than generator reactances; are more efficient in controlling the current flow, and have the advantage of localizing the effect of a fault to one or more sections of the busbars. They have the disadvantage that, under normal conditions of operation, the current flow across them may cause an undesirable drop in voltage.

The ideal system of bus reactances would afford maximum protection to service and equipment in emergencies but, under normal operating conditions, would give minimum voltage difference between various points in the busbars. The straight bus, the ring bus, and the ring and transfer bus approach this ideal condition in the order named.

Reactance coils in each feeder circuit are extremely effective in limiting the flow of current into a short circuit on the feeder and in isolating the effects of this short circuit from the other parts of the system.

THE PRESENT tendency in power generation is toward larger central stations and larger units and consequent concentration of large amounts of power on one set of busbars. The reasons for this tendency are, the smaller total capital investment required, the lower operating expenses, and the higher operating efficiencies obtained.

That the concentration of a large amount of generating capacity on one set of busbars can give rise to very destructive effects, in cases of accidental short circuits on busbars or on feeders, has been proved by the experience at some time or other of many of the larger central stations. A short circuit or a ground on a feeder, the failure of a current transformer, the hanging of an arc at a fuse, or the throwing on the busbars of a generator slightly out of phase, have resulted in tearing out generator and transformer windings, blowing oil switches to pieces, and even in the destruction of masonry walls. In milder

cases these effects are shown by distortion of end windings on generators and transformers and by oil throwing, or tank distortion, of oil switches.

To limit the flow of energy into faults, reactance coils have been employed in various ways. It is the purpose of this paper to show some of the ways in which these reactances may be employed and the limits of economical application in each of the systems discussed.

Various Arrangements of Reactance Coils

The reactance which is inherent in the design of all a-c. generators may be augmented by additional reactance coils located as follows:

a. In the generator leads.
b. In tie lines between different power stations.
c. Between different sections of the station busbars.
d. In the station busbars between adjacent generator connections.
e. Combinations of any of the above systems.
f. In feeder circuits.

Generator Reactance—Inherent or External

Reactance inherent in the design, or reactance coils in the external leads, of generators, afford protection to the armature windings by limiting the amount of current that can flow through these windings, in the case of a short circuit on the busbars or feeders. The amount of instantaneous current flow varies, approximately, inversely as the total amount of the reactance.

The amount of current which can flow into a short circuit is limited by the amount which can flow from the generators. These reactances are therefore useful in limiting the total amount of current flow into a short circuit and the resultant destructive effects at this point.

There are two objections to the use of large reactance coils in the generator leads for limiting the total kv-a. which can flow into a short circuit on a very large system. The first of these is that, from the nature of their location, they must be designed to carry the entire current output of the generators and hence their kv-a. ratings are high and they become expensive and bulky.

The second objection is, that a short circuit on any section of the busbars will cause a drop in voltage at all points on the

busbars of approximately the same degree, and the service on *all* feeders distributing from this station will suffer in consequence.

It therefore appears that the most important function of reactance coils in the generator leads is to protect the generator windings.

Sectionalizing Reactances

Reactance coils may be placed in tie lines between stations, in the busbars between different sections of the same station, or even in the busbars between adjacent generating units connected to the busbars. The function of these sectionalizing reactances is to permit the parallel operation of, and the free exchange of current between, different parts of the system, and at the same time limit the amount of current which would otherwise flow from all sections into a short circuit on any one section. If reactance coils are suitably selected, it is possible so to confine a fault to the section in which it originates, that adjacent sections are not seriously affected and hence service is impaired only on that section in which the fault originates.

Reactance coils for this service are, as a rule, not designed to carry the full current generated, and are therefore less expensive and less bulky than those placed in the generator leads.

Where considerable power must be transmitted over these reactance coils, the amount of reactance that can be employed is limited by the permissible voltage drop across them. For instance, in a large station, during periods of light load, it will be desirable to carry the entire load on one or two generators and distribute from feeders all along the bus. If the running generators are at one end of the busbars and if the power distributed from the other end of the busbars must pass over several sectionalizing reactance coils, there may be, in the case of large reactances and low power factor, a considerable voltage drop across these reactances and a resulting difference in voltage between the two ends of the busbars.

It is obvious from the above that the best results will be obtained from a judicious combination of generator reactances to protect the machines, and sectionalizing reactances to protect the service.

Busbar Systems

In laying out the busbar system for a large new power station the designing engineer should therefore consider, in addition to safety, simplicity, and flexibility, the adaptability of the system

to the installation of sectionalizing reactance coils. Some of the more common systems of arranging busbars are shown diagrammatically in Fig. 1. These are:

a. Single straight bus.
b. Double straight bus.
c. Single ring bus.
d. Double ring bus.
e. Single straight bus and direct feed.
f. Single ring and single straight bus.

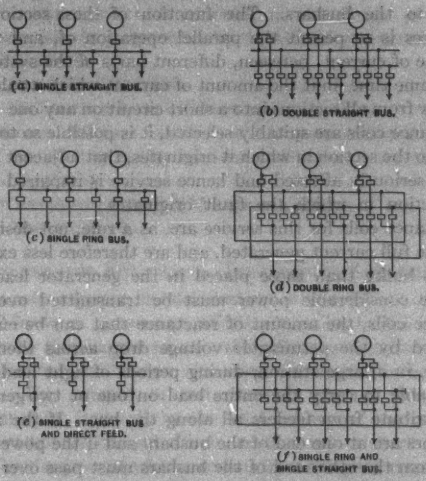


FIG. 1—SINGLE-LINE DIAGRAMS OF TYPICAL SYSTEMS OF CONNECTION

ANALYSIS OF APPLICATIONS OF REACTANCE COILS

For analyzing the effects of reactance coils as outlined above a power station of nine (9) generators has been assumed. It is further assumed that these generators are of the same size and design and that each one has 10 per cent inherent reactance. Based on these assumptions, a series of curves has been plotted to show the effect of variations in the size and location of the reactance coils.

In a large station, when all of the generating units are not in

operation, it is usually desirable from the boiler room and coal handling point of view, to operate adjacent machines, and, with a few exceptions that are specially noted, the curves are based on such operation. It is further assumed that the power is evenly distributed from the different sections of the busbars.

Where kv-a. values are given they are based on an assumed rating of 25,000 kv-a. for each generator; the curves and all other values are general, as far as kv-a. rating is concerned, and can be applied to generators of any rating. All reactance ratings, except feeder reactances, are given in the percentage reactive voltage drop that would occur if the rated current of one generator were passed through them.

For the sake of brevity, the computations used in deriving the curves have been omitted. The methods of derivation are, however, exceedingly simple and for the benefit of those who wish to verify the curves, typical computations are given in an appendix.

Reactance in Generator Leads

Fig. 2 shows the relation between per cent reactance in generator leads and short-circuit current on the busbars, for different assumed values of reactances, with 1 to 9 generators connected to the busbars.

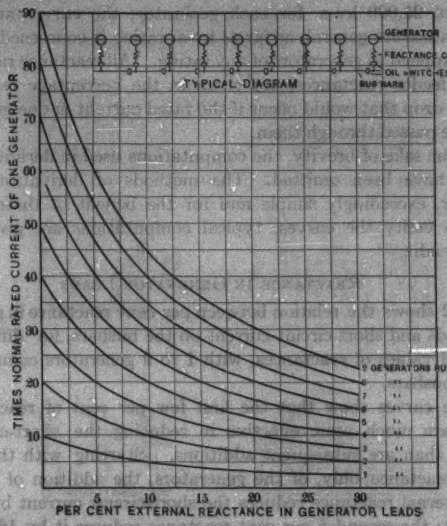
These curves show that the first few per cent of reactance added are much more effective in reducing the short-circuit current than are subsequent additions. Starting with the inherent reactance, only, of the generators, the addition of 5 per cent external reactance reduces the short-circuit current by 33⅓ per cent; the second 5 per cent reactance reduces it by 16⅔ per cent; the third 5 per cent reactance reduces it by 10 per cent; the fourth 5 per cent reactance by 6⅔ per cent, etc., until the effect of further additions becomes infinitesimal.

With nine 25,000-kv-a. generators in operation it will be noted that each generator requires 20 per cent reactance in its leads, a total of 45,000 kv-a., to limit the current flow to 30 times the rated current of one generator, or to 750,000 kv-a., based on actual current flow and normal voltage of the system. The value 750,000 kv-a. has been selected as a limiting value because it approaches the maximum rupturing capacity specified by one or two of the large manufacturers for the heaviest duty oil switches now on the market.

REACTANCE IN BUSBARS—SINGLE OR DOUBLE STRAIGHT BUS

Figs. 3, 4, and 5, show the relation between per cent reactance in busbars and short-circuit current on the busbars, assuming nine generators running. Each figure shows four curves:

Curves (*a*) and (*b*) assume a fault developing in the center of the busbars, while (*c*) and (*d*) assume a fault at the end of busbars.



Relation between per cent external reactance in generator leads and maximum current flow into a short circuit on the busbars.
Inherent reactance of each generator = 10 per cent.
Reactance in busbars = 0.

FIG. 2

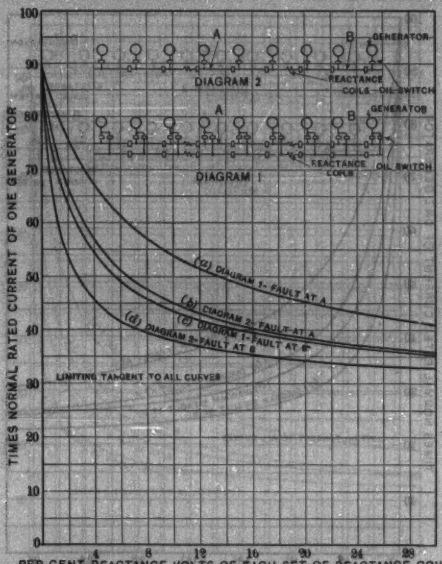
Curves (*b*) and (*d*) apply to a single straight bus, while curves (*a*) and (*c*) apply to a double straight bus.

Fig. 3 covers reactance in busbars between groups of three generators per group.

Fig. 4 covers reactance in busbars between groups of two generators per group, and in this case the number of generators has been increased to ten to obtain a symmetrical arrangement.

Fig. 5 covers reactance in busbars between the individual generators.

With double busbars there are required twice as many reactance units as with single busbars, but inasmuch as with the double bus each reactance carries but one-half the current carried by each reactance in the single bus, the total kv-a. required will be the same in either case.

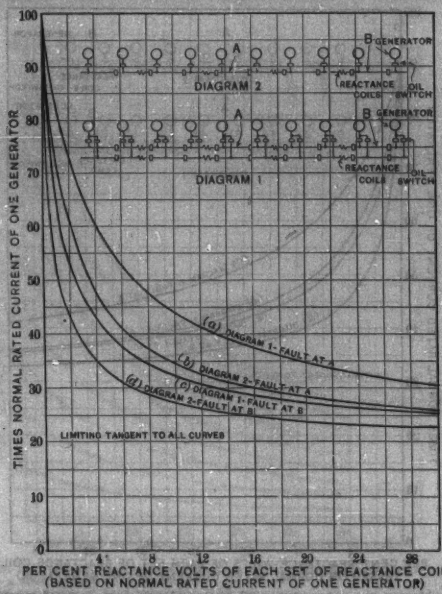


Relation between per cent reactance in busbars and maximum current flow into a short circuit on the busbars.
Type of Bus: Straight, single and double.
Reactance coils located between groups of three generators per group.
Inherent reactance of each generator = 10 per cent.
External reactance in each set of generator leads = 0.
Number of generators running = 9.

FIG. 3

Comparing similar curves in Figs. 3 and 5, it will be seen that a given total per cent in reactance has a greater choking effect when distributed between adjacent generators than when more concentrated by placing between groups of three generators per group, and that this difference increases as the amount of reactance is increased. For example:

Comparing the (*b*) curves, 16 per cent total reactance divided into two units of 8 per cent each will prevent the current from exceeding 48 times normal rated current of one generator, while this same reactance divided into eight units of 2 per cent each will limit the current to 44.5 times. Likewise 32 per cent re-



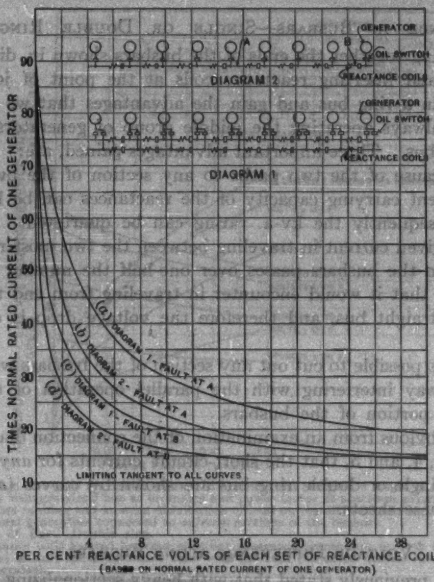
Relation between per cent reactance in busbars and maximum current flow into a short circuit on the busbars.
Type of Bus: Straight, single and double.
Reactance coils located between groups of two generators per group.
Inherent reactance of each generator = 10 per cent.
External reactance in each set of generator leads = 0.
Number of generators running = 10.

FIG. 4

actance in two units of 16 per cent each, limits the current to 40.5 times, while in eight units of 4 per cent each it will limit the current to 33 times. 60 per cent reactance in two units of 30 per cent each limits the current to 36 times, while in eight units of 7½ per cent each it will limit the current to 25.5 times.

Considering again the case of the nine 25,000-kv-a. genera-

tors in which the short-circuit current is limited to 30 times the normal rated current of one generator, and assuming all reactance coils to have one-half the current carrying capacity of the generators, and remembering that the kv-a. reactance rating varies as the square of the current, it will be seen that under the worst condition of short circuit ((*a*) curves) with reactances between



Relation between per cent reactance in busbars and maximum current flow into a short circuit on the busbars.
Type of Bus: Straight, single and double.
Reactance coils located between *adjacent* generator connections.
Inherent reactance of each generator = 10 per cent.
Exteral reactance in each set of generator leads = 0.
Number of generators running = 9.

FIG. 5

groups of three generators, infinite reactance would be required; with reactances between groups of two generators the reactance required is $0.32 \times 8 \times \frac{25{,}000}{4} = 16{,}000$ kv-a.; with reactances between adjacent generators the reactance required is $0.10 \times 16 \times \frac{25{,}000}{4} = 10{,}000$ kv-a.

There is another advantage to be gained by placing reactances between adjacent generators, namely; in case of a short circuit the full effect of the so-called "hammer blow" is felt by but one generator—the one on the same section with the short circuit—while all other generators are more or less isolated from this trouble by one or more sets of reactance coils.

Reactance in Busbars—Single or Double Ring Bus

By tying together the ends of the busbars shown in diagram Fig. 5, and inserting reactance coils at the point of joining, we obtain a ring bus and gain the advantages that we would get by always operating the middle group of generators on a straight bus. Three important advantages gained, are:

1. Because of the two paths to any section of the busbars, the current carrying capacity of the reactances can be halved and consequently the kv-a. rating can be quartered.

2. A given current in traveling between the two most remote points on the busbars passes over one-half the number of reactances that it would encounter in traveling from end to end of the straight bus, and therefore the voltage drop is cut in half.

3. It is possible to cut out any section of the busbars without in any way interfering with the parallel operation of the remaining portion of the busbars.

It is obvious from an examination of the connection diagrams in Fig. 3, 4, and 5, that the short-circuit currents for *any* point on the single or double ring bus are shown by curves (*a*) and (*b*) on these sheets.

Voltage Difference along Busbars

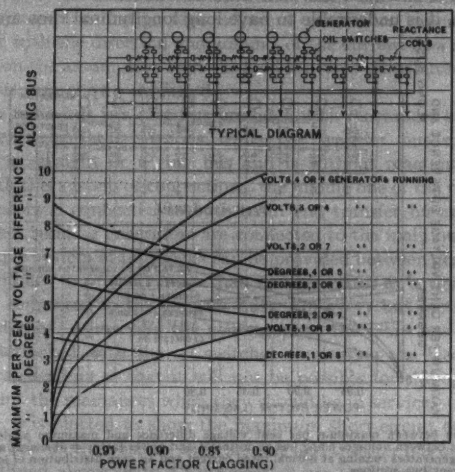
It was previously stated that with heavy sectionalizing reactance coils in the busbars it is possible, under certain conditions of operation, to get an objectionable difference in voltage along the busbars.

Fig. 6 is plotted to show the maximum voltage difference and the maximum angular difference of voltage that will exist along the busbars with a double ring bus and 12 per cent reactance between adjacent generator sections in each bus, with one to nine generators running at a power factor between 1.0 and 0.8 lagging, and an even distribution of load along the busbars. It will be noted that a maximum voltage difference of 9.9 per cent can exist with four or five machines running at 0.8 power

factor, and a maximum angular difference of 8.75 degrees can exist with the same number of machines running at unity power factor.

Crossed Generator Leads

Fig. 7 differs from Fig. 6 in that adjacent generator leads do not go to adjacent sections of the busbars but are cross-connected



Relation between maximum voltage difference and maximum angle of displacement between voltages along bus as ordinates and power factor as abscissas, assuming adjacent generators running and an even distribution of load on the different bus sections.
Adjacent generators connected to *adjacent* sections of the busbars.
Type of Bus: Double ring.
Reactance coils located between adjacent generator connections in both buses.
Rating of each set of reactance coils = 12 per cent (based on normal rated current of one generator)
Inherent reactance of each generator = 10 per cent.
External reactance in each set of generator leads = 0.
Number of generators running = 1 to 9.

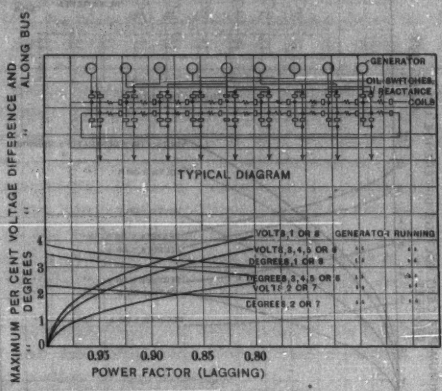
Fig. 6

in such a manner as to give minimum voltage difference along the busbars when operating adjacent generators. The order of connecting to the busbars is shown by the diagram of connections in Fig. 7. It will be noticed that with this arrangement of leads the maximum voltage difference along the bus is materially reduced; the maximum point on Fig. 7 being 4.2 per cent as against 9.9 per cent on Fig. 6. An inspection of the diagram

also shows that the short-circuit curves shown by (*a*) and (*b*) on Fig. 5 also hold for this case of cross-connected generator leads.

This arrangement of generator leads has certain disadvantages, the chief of which is that some of the leads of the older generators have to be changed to different locations on the busbars as the station is extended and new units are added.

Also, it is undesirable to have long longitudinal runs and sev-



Relation between maximum per cent voltage difference and maximum angle of displacement between voltages along bus as ordinates and power factor as abscissas, assuming adjacent generators running at normal rated current and an even distribution of load from the different bus sections.

Alternate generators connected to *adjacent* sections of the busbars.
Type of Bus: Double ring.
Reactance coils located between adjacent generator connections in both buses.
Rating of each set of reactance coils = 12 per cent (based on normal rated current of one generator)
Inherent reactance of each generator = 10 per cent.
External reactance in each set of generator leads = 0.
Number of generators running = 1 to 9.

FIG. 7

eral crossings of generator leads; these runs should be as short and direct as possible.

PROTECTION VERSUS REGULATION

The curves have shown that with reactance coils permanently connected in the busbars, the larger the reactance the better the protection against short circuits. On the other hand, the larger the reactance the worse the voltage regulation along the busbars. It is therefore evident that it would be desirable to adopt some method of shunting the reactance coils when they

are not needed for protection. The most direct way of accomplishing this would be to short-circuit the reactances. This introduces an oil switch for each set of reactance coils.

Ring and Transfer Bus

A simple method of shunting reactance coils when they are not needed is by the use of a ring and transfer bus. The connections of this system for one to nine adjacent generators running, together with the direction and amount of the current flow in each path, on the assumption that the load is evenly distributed along the bus, are shown in Fig. 8.

The main bus is a ring bus provided with reactances between adjacent generator sections, while the transfer bus may be either a straight or a ring bus and is without reactances.

With this system of connections, the middle one of the running generators is connected to both main and transfer buses, while all other running generators are connected to the main bus only. A simple system of interlocks can be provided between generator oil switches to prevent more than one generator at a time from being connected to the transfer bus. On every bus section the oil switches connecting the generators to the main bus should be interlocked with the oil switches connecting the feeders to the transfer bus so that it will not be possible for the operator to shunt the reactances when they should be in service.

Fig. 9 is plotted to show the maximum short-circuit currents obtainable on the busbars with the ring and transfer bus operated as outlined above, with 12 per cent, 8 per cent and 6 per cent reactances respectively between adjacent generator sections in the ring bus, with one to nine adjacent generators running.

From Fig. 9 it will be seen that the maximum short-circuit current occurs with eight machines in service. With 12 per cent bus reactances this current may reach 30.8 times the normal rated current of one generator. These curves show that the short-circuit current is less with nine machines running than with four, five, six, seven, or eight machines running. The reason for this is, that in the latter cases there are two parallel paths between some portions of the system, while with nine generators there is but one path.

Fig. 10 is plotted to show the maximum voltage difference that will exist along the busbars with the ring and transfer bus operated as outlined above, with 12 per cent, 8 per cent and 6 per cent reactances, respectively, between adjacent generator

sections in the ring bus, assuming one to nine adjacent generators operating at 1.0 to 0.8 lagging power factor and an even distribution of load along the busbars.

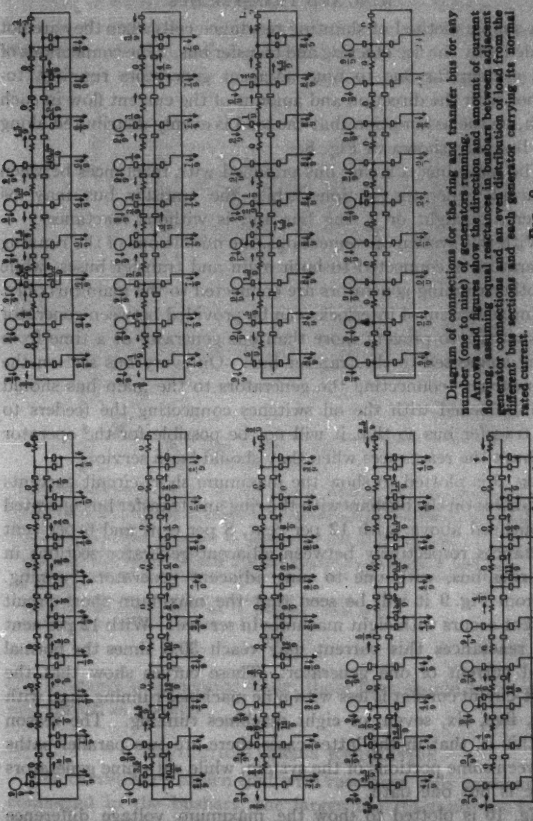


Diagram of connections for the ring and transfer bus for any number (one to nine) of generators running.
Arrows show the relative amount of current flowing, assuming equal reactances in busbars between adjacent generator connections and an even distribution of load from the different bus sections and each generator carrying its normal rated current.

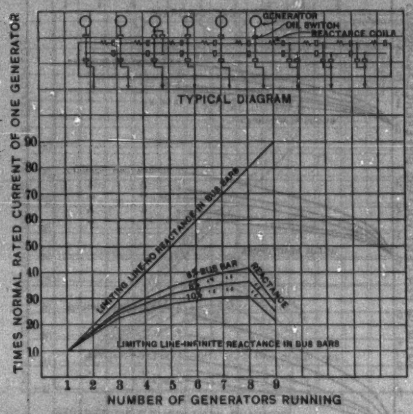
FIG. 8

From Fig. 10 it will be seen that the maximum voltage drop occurs with six generators running, but that this is considerably less with a larger or a smaller number of generators in service.

With 12 per cent bus reactances, the maximum voltage difference along the busbars under the conditions specified is 5 per cent.

If other than adjacent generators are operated it is possible with a given bus reactance to obtain higher values of short-circuit currents than are shown in Fig. 9 and lower maximum voltage drops than are shown in Fig. 10.

Fig. 11 is plotted to show the values of short-circuit current



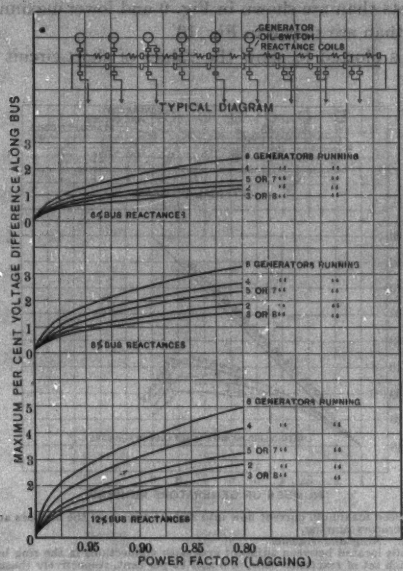
Relation between maximum current flow into a short circuit on the busbars and number of adjacent generators running.
Type of Bus: Ring and transfer.
Reactance coils located between adjacent generator connections in the ring bus only.
Ratings of each set of reactance coils, 6, 8 and 12 per cent, respectively (based on normal rated current of one generator)
Inherent reactance of each generator = 10 per cent.
External reactance in each set of generator leads = 0.
Number of generators running = 1 to 9.
Method of Operating: The middle one of the running generators to be connected to both main and transfer bus; all other generators are to be connected to main bus only. On each section the oil switch between generator and main bus to be interlocked with the feeder switches between feeders and transfer bus, so that they cannot both be closed at the same time; feeder switches closed on both buses when generator on same section is not connected to bus.

FIG. 9

that would be obtained if the generators were so selected as to give the maximum possible values, with bus reactances chosen at 6, 8, 12, 20, and 30 per cent, respectively. With 12 per cent reactance it will be noted that the short-circuit current may reach nearly 38 times the normal rated current of one generator. The reason for the higher values of short-circuit current in this case is that there are several parallel circuits between the ring

and the transfer bus, so arranged as to give the path of least reactance between these buses.

Obviously this method of operation is abnormal and the curves of voltage drop are therefore not of special interest.



Relation between maximum per cent voltage difference along bus and power factor, assuming adjacent generators running at normal rated current and an even distribution of load from the different bus sections.

Type of Bus: Ring and transfer.

Reactance coils located between adjacent generator connections in the ring bus only.

Ratings of each set of reactance coils 6, 8 and 12 per cent respectively, (based on normal rated current of one generator)

Inherent reactance of each generator = 10 per cent.

External reactance in each set of generator leads = 0.

Number of generators running = 1 to 9.

***Method of Operating*: The middle one of the running generators to be connected to both main and transfer bus; all other generators are to be connected to main bus only. On each section the oil switch between generator and main bus to be interlocked with the feeder switches between feeders and transfer bus, so that they cannot both be closed at the same time; feeder switches closed on both buses when generator on same section is not connected to bus.**

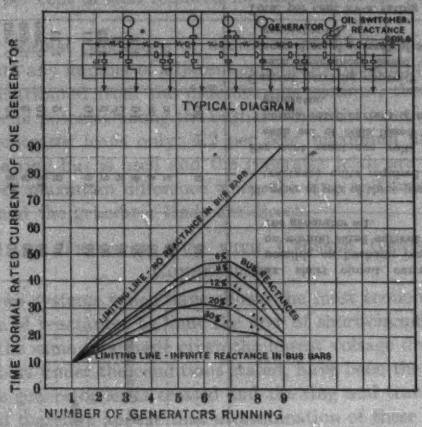
Fig. 10

Current-Carrying Capacity of Reactances

It was stated above that reactance coils in generator leads must be designed to carry the normal rated generator current. It was shown that in the ring bus the bus reactances might be

of one-half the current-carrying capacity of the reactances used on the straight bus.

Fig. 8 shows that with any number of adjacent generators in operation at their normal rated loads and the station load evenly distributed from the different sections of the busbars, the maximum current flow across any bus reactance coil is 5/9 the normal rated current of one generator.



Relation between maximum current flow into a short circuit on the busbars and number of generators running, generators being selected to give the greatest possible short-circuit current.

Type of bus: Ring and transfer.

Reactance coils located between adjacent generator connections in the ring bus only.

Ratings of each set of reactance coils, 6, 8, 12, 20 and 30 per cent respectively (based on normal rated current of one generator)

Inherent reactance of each generator = 10 per cent.

External reactance in each set of generator leads = 0.

Number of generators running = 1 to 9.

Method of Operating: The middle one of the running generators to be connected to both main and transfer bus; all other generators are to be connected to main bus only. On each section the oil switch between generator and main bus to be interlocked with the feeder switches between feeders and transfer bus, so that they cannot both be closed at the same time; feeder switches closed on both buses when generator on same section is not connected to bus.

FIG. 11

The proper current-carrying capacity for any other system may be found by constructing diagrams similar to those of Fig. 8.

COMPARISON OF SYSTEMS—TABULATION

The accompanying tabulation shows the number, size, and effect on voltage regulation of reactances used on each of the systems discussed in this paper, based on a limiting short-cir-

System of Arranging Reactances	Max. short circuit current possible on busbars; based on normal rated current of one generator = 1.	Number of sets of three-phase reactance units required.	Per cent reactance volts of each set of coils, based on normal rated current of one generator.	Current carrying capacity of each reactance; based on normal rated current of one generator = 1.	Total per cent kv-a. rating of reactance, based on rating of one generator = 100 per cent.	Total kv-a. reactance, assuming nine 25,000 kv-a. generators.	Max. percentage voltage difference along busbars.
Reactances in Generator Leads	30	9	20	1	180	45,000	0
Reactances in Busbars—Straight bus							
Between groups of 3 generators per group (Single bus)	30	2	∞	2	∞	∞	Not computed
Between groups of 3 generators per group (Double bus)	30	4	∞	1	∞	∞	
Between groups of 2 generators per group (Single bus) } 10 Generators	30	4	16	2.4	368	92,000	
Between groups of 2 generators per group (Double bus) } 10 Generators	30	8	32	1.2	368	92,000	
Between adjacent generators (Single bus)	30	8	5	2.22	197	49,250	
Between adjacent generators (Double bus)	30	16	10	1.11	197	49,250	
Reactances in Busbars, between adjacent generators—Ring bus.							
Generator connections direct (Single bus)	30	9	5	1.11	55.5	13,888	9.9
Generator connections direct (Double bus)	30	18	10	0.555	55.5	13,888	9.9
Generator connections crossed (Single bus)	30	9	5	0.666	20	5,000	4.2
Generator connections crossed (Double bus)	30	18	10	0.333	20	5,000	4.2
Ring and transfer bus, reactances in ring bus only, generator connections direct	30.8	9	12	0.555	33.3	8,333	5

cuit current of approximately thirty times the normal rated current of one generator.

The ring bus with crossed generator leads as per diagram Fig. 7, requires the least reactance and gives the lowest voltage drop along the busbars.

The ring and transfer bus requires 60 per cent of the reactance required by the ring bus with direct generator connections, and 18½ per cent of that required for inserting in the generator leads.

Under normal conditions of operation at 0.8 lagging power factor with any number of adjacent generators running, and load evenly distributed from the different bus sections, there is no difference of potential along the busbars when the reactances are in the generator leads only; 4.2 per cent maximum difference when the ring bus is used and the generator leads are crossed; 5 per cent maximum difference when the ring and transfer bus is used and the generator leads are direct.

Ring and Transfer Bus with Crossed Generator Connections

The two systems which have shown the most economical application of reactances to limit the flow of short-circuit current and at the same time have given the lowest voltage drop along the busbars under the conditions stated, have been the ring bus with the generator leads crossed and the ring and transfer bus. It would therefore appear that a combination of these two systems, in which generators 1, 2, 3, 4, 5, 6, etc., are connected to sections 1, 3, 5, 7, 9, 2, etc., would give still better results.

By consulting Fig. 11 it will be seen that with only five generators running, each bus reactance must be designed to give 20 per cent reactive volts. Under the conditions of operation assumed, each reactance should be designed to carry 0.389 times the normal rated current of one generator. This amounts to 27.2 total per cent reactance based on rating of one generator = 100 per cent. This is greater than the 20 per cent shown by the simpler ring bus with crossed generator leads. Moreover, it can be easily shown that the voltage difference along busbars for the assumed conditions is not improved by this connection. This system can therefore be dropped from further consideration.

Feeder Reactances

As grounds and short circuits are more commonly experienced on feeders outside the power station than on the busbars inside

the power station, an additional protection to service and apparatus is afforded by placing reactance coils in the circuit of each feeder connected to the busbars.

As has been previously shown, reactance in the busbars tends to confine the effect of short circuits to the section of bus on which they occur. By placing reactance coils in the feeders we place an additional barrier between the source of trouble on the feeder and the section of busbars to which this feeder is connected. This point will perhaps be best illustrated by considering the case of a short circuit on a feeder just outside the power station and determining the effect of this short circuit on various sections of the busbars both with and without feeder reactances. For this example assume nine 25,000-kv-a. generators in service on the ring and transfer bus system (which with

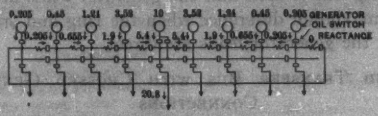


Diagram showing maximum amount and direction of flow of current in all parts of the system where feeder reactances are not used, assuming a short circuit on any feeder.
Type of Bus: Ring and transfer.
Reactance coils located between adjacent generator connections in the ring bus only.
Rating of each set of bus reactance coils = 12 per cent (based on normal rated current of one generator)
Inherent reactance of each generator = 10 per cent.
External reactance in each set of generator leads = 0.
Number of generators running = 9.

FIG. 12

nine generators becomes a pure ring connection), 12 per cent reactance between each generator and a short circuit on any feeder.

Fig. 12 shows the direction of flow and the amount of current in each set of generator leads and on each section of busbars where feeder reactances are not used.

Fig. 13 shows similar results where each feeder is provided with 3 per cent reactance based on a normal rating of 5000 kv-a.

A comparison of Figs. 12 and 13 shows that the addition of the feeder reactance has reduced the short-circuit current into a feeder from 20.8 times to 5.05 times the normal rated current of one generator; *i.e.*, to less than $\frac{1}{4}$ of its former value. The current flowing from each generator and in every part of the busbars is also reduced to 1/4 of its former value.

It is obvious from Fig. 13 that, with the relatively small amount of current flowing into a feeder short circuit, and the relatively small amount of this current which flows from bus sections adjacent to the fault, the disturbance in voltage on the system will be local only. On the section of the busbars to which the faulty feeder is connected, the drop in voltage will be only about 25 per cent. At 0.8 power factor, 5000 kv-a. flowing over 3 per cent reactance will give a voltage drop of approximately 1.9 per cent.

General Comments

The question naturally arises, what effect will a voltage difference along the busbars have on the service of the system?

On a power system, the feeders of which go direct to light and power distributing transformers, it is desirable that the voltage

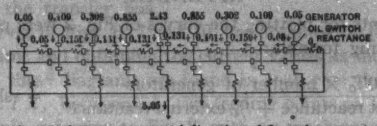


Diagram showing maximum amount and direction of flow of current in all parts of the system where reactance coils are placed in each feeder circuit, assuming a short circuit on any feeder.

Type of Bus: Ring and transfer.
Bus reactance coils located between adjacent generator connections in the ring bus only.
Rating of each set of bus reactance coils = 12 per cent (based on normal rated current of one generator)
Rating of each set of feeder reactance coils = 3 per cent (based on 5000 kv-a. flowing)
Inherent reactance of each generator = 10 per cent.
External reactance in each set of generator leads = 0.
Number of generators running = 9.

Fig. 13

on the busbars be as nearly constant as possible. When the voltage drop between the busbars and the center of distribution is large, it is usually taken care of by placing feeder regulators in the feeder circuit at the power station end and boosting the voltage of the feeder by an amount equal to the drop. This system of distribution is not adapted to handling economically the output of very large power systems and therefore does not call for the extensive application of reactance coils.

On power systems such as exist in most of our largest cities, it is customary to first transmit the power, at voltages ranging from 6600 volts to 22,000 volts, to substations conveniently located, transform to a lower voltage at the substations, and then distribute. Because of the greater distances of transmission, and the double transformation between the power station and the

customers' premises, feeder regulators are practically necessary on the distribution feeders leaving the substations. Any difference in voltage on the busbars will be equalized by these regulators before the power is delivered to the customers' premises.

In this country the feeders between the largest power stations and substations are usually operated as radial feeders, that is, are not tied together at the substation end. This condition of operation is assumed in this paper. If feeders were paralleled at the substations, there would be two tendencies:

1. A tendency to shunt the bus section reactances; and
2. A tendency for a feeder from the section of the busbars having the higher voltage to carry more current than a feeder connected to a section of lower voltage. A discussion of these interesting features, is, however, beyond the scope of this paper.

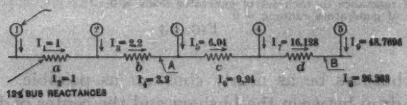
APPENDIX

The points for plotting the curves of Fig. 2 were obtained by the following formula:

$$\frac{100\% \times \text{number of generators}}{\%\ \text{inherent reactance} + \%\ \text{external reactance}} = \text{short-circuit}$$

current expressed in times normal rated current of one generator.

The points for plotting the curves of Figs. 3, 4, 5, 9 and 11 and the values shown on Figs. 12 and 13 were obtained by the following typical method:



Consider first a fault at A.

Assume $I_1 = 1$. This current flows over reactances a without additions or subtractions and therefore

$I_2 = I_1$

$I_3 \times 10 = (I_1 \times 10) + (I_2 \times 12)$, or $I_3 = 2.2$

$I_4 = I_3 + I_2 = 3.2$

$I_5 \times 10 = (I_3 \times 10) + (I_4 \times 12)$, or $I_5 = 6.04$

With fault at A we know that generator 3 with 10 per cent inherent reactance will give 10 times normal rated current.

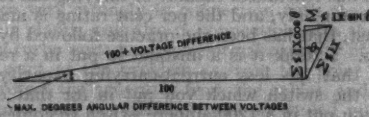
Therefore, raising all the current values by the ratio of 10/6.04 and noting that from symmetry, the current over reactance

c is the same as that over reactance b, we get the short-circuit current at $A = \frac{10}{6.04}[(2\times3.2) + 6.04] = 20.6$ times normal rated current of one generator.

Following the same process we get $I_B = 48.7696$, but knowing $I_B = 10$ times normal rated current of one generator, the actual short-circuit current at $B = \frac{10}{48.7696}(48.7696 + 26.368) = 15.4$ times normal rated current of one generator.

The current flowing in the various portions of the busbars as shown in Fig. 8, is obtained by finding points on the ring bus from which there are two symmetrical paths of equal reactance to the transfer bus, and considering that the current not sent out direct from the generators over the feeders follows these paths to the transfer bus.

The curves of Figs. 6, 7 and 10, are obtained by first drawing the diagrams and obtaining the current values as shown by Fig. 8. From these diagrams are found in each case the maximum value of $\Sigma I X$, between any two feeding points on the busbars. For example, referring to Fig. 8, with six machines running the maximum $\Sigma I X = \frac{1.5}{9}X + \frac{4.5}{9}X = \frac{6}{9}X$. By referring to the other eight diagrams in this figure it will be seen that $\Sigma I X$ is maximum with six machines running. The voltage difference and the degrees angular displacement between voltages are then found by the following diagram:



A very slight error is introduced by considering $\Sigma I X$ a straight line, because, in reality, each component has a slight angular displacement from every other component. The effect of this error on the curves is, however, unappreciable.

DISCUSSION ON "PROTECTIVE REACTANCE IN LARGE POWER STATIONS" (LYMAN, ROSSMAN AND PERRY), NEW YORK, FEBRUARY 25, 1914.

Philip Torchio: The authors have assumed that the generators have 10 per cent internal reactance, and some of the curves have been figured on that percentage. Although there may be modern machines that are being designed with the object of high internal reactance in view which have an internal reactance as high as stated, the great majority, or practically all of the machines in central stations at the present time, have internal reactance considerably smaller than 10 per cent. On 25-cycle machines the internal reactance will be 5 per cent or less. In such cases if you had assumed 5 per cent internal generator reactance, the figures and curves presented would have been considerably different and would have shown that there is little gain in installing bus reactances in excess of 12 to 15 per cent.

This large amount of reactance in bus sections is somewhat of an objection in most of the conditions where you have the feeders radiating from the different sections of busbars into substations and being multiplied in the substations, since these parallel feeders form a shunt to the reactance. If you have three sections of busbars divided by 20 per cent reactances, and feeders from these buses paralleled on substation buses, if you have trouble on one section, the protection that you get from this 20 per cent reactance is minimized by the impedance of the shunting of these feeders, and the effectiveness of these high reactances will be reduced to 12 to 15 per cent.

The authors point out the difficulties of having these reactances too high on account of having a phase displacement across the reactance which is shunted by feeder circuits and causing currents to flow through these by-paths. I do not think the paper covers fully the size of the reactances required, as they consider the bus reactances capable of carrying full-load current of one generator only, and the per cent rating is made on that basis; at least, that has been the practise followed by a number of engineers. I think it is a mistake to put in a reactance in the busbar that has less current-carrying capacity than the capacity of the switch which you put in for that connection. That is, if you put in a 1200-ampere switch to connect the busbars, the reactance which is in series with the switch should have a continuous carrying capacity of 1200 amperes.

I think the two points I make would tend to bring about a rather small reactance per section, that is, the per cent reactance, rated in the function of the carrying capacity to the switch, which I imagine usually is determined by the amount of maximum power you expect to transmit on that line from one section to another.

I regret that the paper does not cover the field of feeder reactances as fully as the busbar reactance, although it has been mentioned to some extent. It would have been quite an addition to have a complete treatment of the feeder reactance, which is, I think, one of the greatest mediums for securing protection of our high-tension systems.

W. S. Moody: The principal requirement of such reactance is that it shall be extremely safe and substantial. It is put in to protect at times of extreme trouble, and unless it is absolutely able to handle trouble within itself at such times, then perhaps it had better not be there at all. The heavy forces that have to be taken care of in the magnetic strains and the tremendous amount of power that has to be absorbed momentarily, all require the greatest rigidity and the greatest simplicity, and unusual factors of safety in every respect, in such a device.

With reference to the use of reactances, rather than the devices themselves, it seems to me there are two broad considerations that we want to remember. One is that all power these days is distributed on a constant-potential system. Consequently, an amount of reactance that interferes appreciably with maintenance of constant potential is prohibitive, but, on the other hand, we cannot have too small an increase of current at times of trouble and short circuits. Consequently, the amount of reactance and the location of the reactance, so long as they do not interfere with the maintenance of constant potential, cannot be used too freely, because even if the apparatus is quite capable of standing short circuits the operation of the system is that much less disturbed, to the extent to which the current at the time of trouble can be limited. So, outside of the financial consideration of the cost of the reactance, too much reactance cannot be introduced, in the sectionalizing of a system, so long as the maintenance of approximately constant potential is not interfered with.

Henry G. Stott: This is a subject which has been brought to our notice very strongly in connection with the redesigning of one of our plants, and also in connection with the introduction of large turbo units having a normal capacity of 30,000 kw. each. We went at the problem as from the point of view of trying to protect the generator from the cables, and to protect the generators from one another, and we ended up by trying to protect cables from the generators. The problem, therefore, was entirely transposed. The generator is pretty well able to take care of itself, but the instantaneous currents, which are reached through the normal action of having a number of these machines (we used five in our calculations) in multiple on the busbars, feeding out to a number of substations, with five and seven feeders in parallel, rise to such enormous values, going up to about 60,000 or 70,000 amperes at 11,000 volts, that we immediately began to foresee trouble due to the repulsion and attraction between phases. The

calculations showed, with three-conductor No. 000 feeder, subject to short circuit of 60,000 amperes, that the dynamic repulsion between conductors per running foot (30.5 cm.) was over one ton. That was one phase of the problem which rather startled us, but we were even more startled by finding that the calculation showed very high temperatures would be reached before any oil switches so far made, could be opened. We assumed the oil switch could be opened in 12 cycles, on a 25-cycle system—it did not seem safe to assume it would go out faster, on average operation—and we found that in the period of 12 cycles, or less, the temperature rise on such a cable would be over 500 deg. cent.

These are the things which forced us into the use of reactances, and, of course, it is quite obvious that the insulation

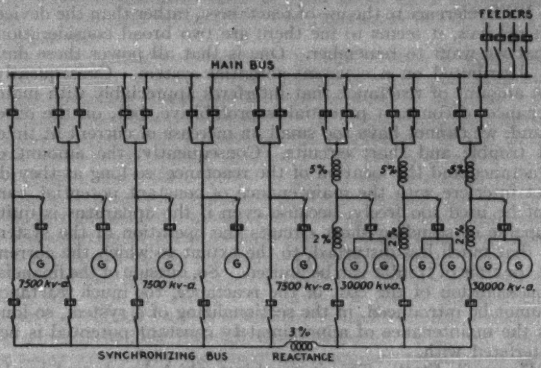


FIG. 1

of the cable would be partially destroyed by even one or two short circuits under these conditions.

We have adopted a scheme slightly different from any of those suggested in this paper, and it is shown clearly in Fig. 1, herewith. The bus normally is open, so each unit feeds out independently; but they are held in parallel through the reactances. As the load falls off, so that one of these units is sufficient to carry it, you close the bus junction switches and shut down the machine. The result is that there is no more reactance in one section than in another. The short-circuit currents in this arrangement work out very advantageously, also; the last calculation showed maximum short-circuit current of not more than 20,000 amperes, which is quite a contrast, compared to 60,000 amperes. We were forced into the use of reactances, not for the sake of protecting the machine, but to protect the

cable from the heating effect and the dynamic results of repulsion on the feeder.

The design of the reactance I think is quite important. It should be one which, as Mr. Moody said, is extremely substantial and practically indestructible from the heat point of view. That is a question yet to be settled, whether it will stand the shock and the high temperatures which will result on certain combinations. The ideal solution of the question we found was in use of individual reactances in the feeder, and we found also, as the result of that discovery, that we would have to build a separate plant to hold the reactances, and that did not seem to be quite feasible at this time, considering the present value of real estate. So the scheme shown is simply a compromise between bus reactance and individual reactance in each feeder, but I think there is no doubt that the ideal solution is an individual reactance in each feeder, and none in the station. However, in large cities that is obviously out of the question, where real estate and buildings are so expensive.

Paul M. Lincoln: There is one point, in regard to the use of reactance, which in a great many discussions is lost sight of, and that is the transient period. If we assume 10 per cent reactance, and 100 per cent voltage, the maximum instantaneous current which can flow through the circuit is not ten times full-load current, but twenty times. If you hit the wave in the right place you will get transient conditions which will give twenty times full-load current. It rapidly goes down to ten times full-load current. If one takes account of transient conditions he gets twice as much current as he will under steady conditions.

Taking time along a horizonatal line, it is well known that during the transient period the voltage waves will become symmetrical, around a logarithmic curve, that is, asymptotic to the X axis, the greatest departure of the logarithmic curve from the X axis being just exactly the full voltage.

That is a condition which, unfortunately, most writers on this subject do not take into account. When, for instance, the authors of this report say so many times full-load current of one generator, we do not know whether they mean to take into account the transient condition or not, but if they do not consider the transient condition, it is easily seen that the worst condition may give a current as high as double the value which is named.

I believe that we all, after we have analyzed this problem, will take exactly the same attitude that Mr. Stott has taken. The intention at first invariably was to get something to protect the generators, because it was the generators which suffered in the early days. Now, we have gotten around the generator, know how to protect it, how to build a generator so that it is self-protective, and now the problem is to protect the service from the rush of current which comes out of the generator. It is now the service that needs the protection, and not the apparatus, and if

we bear that in mind in the study of this problem I believe it will throw a great deal of light on it.

V. Karapetoff: I was glad to hear Mr. Lincoln mention the transient period of short circuit, because I have felt for some time that we must not allow the generator to exert its full destructive action the very first instant of a short circuit, but must provide something within the generator to take care of this transient condition. The natural thought occurred to me to provide something in the exciting circuit, because the exciting circuit is smaller and lighter than the main circuit.

The most natural solution is to put additional reactance in the exciting circuit. Last week, I asked one of my assistants to make some tests, and while the tests were rather crude, because we had no oscillograph, and merely watched the instantaneous deflection of an ammeter, nevertheless, I think the results clearly show that reactance in the exciting circuit limits the first rush of current and is, therefore, useful. The size of this reactance is much smaller than that required in the main circuit, and what is more important, there is no objection to using iron in this reactance.

We used a small alternating machine in our experiments, and the normal value of the exciting circuit was 2.5 amperes. When the machine is short-circuited under certain conditions, and no reactance is put into the exciting circuit, the instantaneous exciting current (not the armature current) rises from 2.5 to 5 amperes. With sufficient reactance, the increase in the exciting current is only from 2.5 to 4 amperes. We also found a similar reduction in the armature current. The steady value of the short-circuit current, the value which occurs after a few instants, was 75 amperes. Without reactance in the exciting circuit, the instantaneous deflection of the ammeter was as high as 180 amperes, instead of 75—the ammeter first goes to 180, and then goes back to 75, due to that transient condition. With the reactance in the exciting circuit, the deflection is only 144 amperes, that is, it goes to 144, and goes back to 75.

It seems to me that here is a remedy which may be useful, not in replacing reactance in the sections of a-c. buses, but helping, at least, to reduce their size. In other words, I believe that it is not right to leave the generator to exert its full destructive action, but that provision must be made in the exciting circuit to limit this transient phenomenon by a sufficient reactance. If some kind of a constant-current regulator could be introduced in the exciting circuit, with a sufficiently quick action to prevent these sudden rises, then we could not possibly have these rises in the armature circuit, and consequently we would have less destructive action. In Dr. Steinmetz's book on "Electric Discharges, Waves and Impulses," there are several oscillograms given, showing what happens in the first instant of a short circuit on an alternator. The armature current rises instantly to a value much higher than its steady value, and the field current also goes

up, and is an oscillatory and pulsating current. We would not have these oscillations in the armature current, if we could prevent oscillations in the exciting current.

Harry R. Woodrow: I think Mr. Lincoln exaggerated a little the instantaneous rush of current on short circuit. The equation for this current in an inductive circuit is

$$i = \frac{E}{Z}\left\{\cos(\theta-\theta_0-\theta_1) - \epsilon^{-\frac{r}{x}\theta}\right\}, \text{ where } \theta_1 = \tan^{-1}\frac{r}{x}$$

and θ_0 is the angular phase of voltage at start of short circuit which must be at point of zero voltage to give maximum value of the transient term where X/r is large. Hence it requires π radius of electrical time for the transient term to reach its maximum value.

In the time π the transient term $\epsilon^{-\frac{r}{x}\theta}$ drops, so that the maximum peak is considerably below twice the normal. In addition to this, the generator voltage is materially reduced in the time π. From a number of tests on turbo-alternator short-circuits, we have found that the maximum transient peak will not exceed the normal peak by more than 50 to 60 per cent.

It is necessary to protect the generators, circuits, etc., at the time of this high initial peak which occurs in one-quarter to one-half a cycle, as any damage that is to be done is done at the time of maximum peak and hence no shunted resistance or reactance could be put in circuit quickly enough to do any good.

The last speaker recommended the insertion of reactances in the field circuits of generators. Punctures of generator field circuits now occur at times of generator short circuits due to the high voltage. Inserting an additional reactance in the field circuit to permit the field to be blown out within the first quarter of a cycle to reduce the current to one-half of its former value would require a reactance equal to the inductance of the field circuit and would produce a voltage approximately as high as pulling the field circuit without discharge resistances.

Feeder reactance will give by far the greatest amount of protection against the trouble which occurs in feeder circuits, and by far the largest percentage of the troubles will occur in feeder circuits. In the tabulation the authors speak about the reactance limiting the current to 30 times the normal rated full-load current of one generator and they have something like 5000 kv-a. required for the best condition of reactances between adjacent generators. If reactances were installed on feeder circuits of the same system, two-thirds per cent reactance would be sufficient to limit the current to 30 times the full-load current of one generator, which would require about 1500 kv-a. in reactances or less than one-third the amount of bus reactance. This per cent kv-a. saving depends on the

size of feeder circuits, and is proportional to the ratio of size of generator to feeder units.

Cassius M. Davis: The paper under discussion considers an ideal case, namely, where a new generating station is to be put in, and arrangement can be made at the time of installation to lay out the system properly to get the maximum protection. There is one difficulty which usually confronts the engineer on a system which already is in operation and growing; that is, the system may have been laid out some years ago with no anticipation that it would grow to such large capacity; the feeders may be connected to the busbar in a more or less haphazard fashion, and in order thoroughly to protect the service at the various substations several feeders may be run in multiple to substations. As a consequence the system becomes so large that it is necessary to protect it by sectionalizing, and the difficulty arises in placing the reactances so as to get the greatest benefit. With a new system which has a large number of relatively small-capacity generators, or if it is a very large system, where there are a number of large generators, it can be laid out very advantageously along the lines which have been shown in this paper. A much more difficult proposition is the system which has been in operation for some time using small units, when it is decided to replace the small units with much larger ones. The feeders and the feeder switches have been designed and installed merely to carry the feeder current. Now, if the larger units are put in, the currents at time of short circuit are very much larger than previously, and therefore it is necessary either to equip the station with new switches or to protect the system in such a manner that the old switches will be able to take care of short circuits, or, as in the case Mr. Stott has brought out, it is a case of protecting the feeders.

A number of cases like this have recently come up. It has generally worked out that the best arrangement of reactances to give the best protection is a combination of generator and feeder reactances, rather than bus-sectionalizing reactances.

Mr. Stott's illustration (Fig. 1) is a combination of feeder reactances and what we may call synchronizing reactances. Each group of feeders is protected by a single reactance. Then the generator is connected without reactance, and each generator is maintained in synchronism with the others in the station by what may be termed a synchronizing reactance and synchronizing bus. It is purely a case of group feeder reactances, no generator reactance, and a section reactance primarily to keep the generators in synchronism. The station would operate just as well without the synchronizing reactances, the protection would be practically the same, but for reasons of convenient operation the synchronizing feature becomes necessary.

Allen M. Rossman: Mr. Torchio remarked that our assumption of 10 per cent generator reactance was rather high.

We will admit that if we were working up the data for some of the older stations it might be high. But when we worked up these curves, we were planning a new 60-cycle station, and had no difficulty in getting guarantees of 10 per cent reactance in the generators, and so we based our curves on that value.

Mr. Torchio suggests selecting busbar reactances with an ampere rating the same as that of the oil switches in the busbars.

If you will refer to the diagrams in Fig. 8 of the paper you will find a close approximation to the required current rating. We have assumed one generator, two generators, three generators, etc., up to nine generators in operation, each carrying its full rated current. We have assumed that this current is fed out in equal amounts from each of the nine feeders or group feeders. You will find by glancing over the diagrams that in no case do we get higher than five-ninths of the full-load current of one generator through any reactance. This figure, with an allowance for unbalance of feeders, gives the proper current rating for the reactances as well as for the bus section switches.

Mr. Stott has stated that in installing generator reactances at an old station another building might be needed to accommodate them. The space required and the high cost are, I think, the chief objections to the extensive use of generator reactances. Reactances in the generator leads are, in my opinion, best adapted for the protection of the generators themselves, but with the generators that we are buying these days it is not so necessary to provide additional reactances in their leads, because of their high inherent reactance and their improved mechanical construction.

Mr. Woodrow has commented on the question of transient effects, raised by Mr. Lincoln, and I will not say anything further on this subject. The method of deriving the curves, as shown in the appendix, considers only the Ix drop.

Mr. Davis has made some comments about stations which were designed some years ago, and on further growth required the addition of reactances. I might mention that not many of the large city stations built a few years ago were designed to deliver the amount of power we are calling on them to give today, and the application of reactances to these stations may be considered special cases. These older stations designed perhaps ten years ago, or even seven or eight years ago, have to give way to new stations, and it is the application of reactances to these very large stations that our paper is intended to cover.

Referring to Mr. Davis's question as to the rating of the reactances, the rating of the reactance is based on the current times the voltage. If we double the current we get double the voltage, because we have twice as many ampere-turns, and therefore we get four times the reactance, therefore the rating varies as the square of the current.

O. J. Ferguson (by letter): Last summer I had occasion to study the various results to be obtained by putting reactors of various capacities in buses and feeders, with straight and ring buses. Based upon 10 per cent inherent reactance of generators, my general conclusions were as outlined below. It will be seen that they agree in many particulars with those of the paper we are discussing.

1. Additional generator reactors are not necessary.
2. The most effective method of placing reactors is to distribute them in buses and in feeders.
3. Based upon one-half the normal output of a bus section, a 25 per cent reactor is generally sufficient for the bus.
4. A 3 per cent to 5 per cent reactor is advised for feeders.
5. If generators with 10 per cent reactances are fed to buses through transformers having 6 per cent to 8 per cent reactance, the bus reactors may be of lower reactance.
6. It is feasible to install bus reactors of impedance sufficient to sustain synchronous apparatus on bus sections adjacent to the one upon which the fault occurs.
7. Owing to the demands of light-load operation, switches to bridge the bus reactors should be developed and made interlocking with the generator switches so that they cannot remain closed when the reactance is required.
8. The present method of rating a reactor is not wholly successful.

As regards the reactor rating, it is worthy of note that reactors to be placed in feeders or in generator leads present a very reasonable demand that they should be rated in terms of those units.

When bus reactors are used, they are frequently rated in terms of only a part of the normal capability of the adjacent bus section, as, for example, upon the basis of only one of the two or three connected generators. This is only a "local" rating and may lead to confusion and to incorrect comparisons of data, etc.

It is my belief that, inasmuch as reactors are subject to installation under such indefinite conditions, they might well have, beside their specific or local rating, a fundamental rating in terms of volts reactance per 100 amperes at normal frequency. This could be called the "60-cycle reactive constant" of the device.

Alex. E. Bauhan (by letter): The paper gives considerable attention to the subject of voltage differences existing in the various sections of a bus equipped with reactances. This voltage difference of course is ordinarily a very undesirable feature, but under certain operating conditions becomes a highly desirable feature. For instance, consider a hydroelectric system consisting of a generating station and two transmission lines having widely differing voltage regulations. Now it is evident that if flat voltage is called for at the substations and no synchronous condensers are available, it becomes necessary to operate the two transmission lines separately at the generating station end, which is usually undesirable.

However, if the two systems are tied together through a set of reactance coils it becomes an easy matter, by properly adjusting the load and excitation, to regulate the voltage on one system independently of the other and yet keep them in parallel.

This scheme is now being used on a high-voltage transmission system under similar conditions to the above. The regulation of one of the lines is 10 per cent at a maximum load of about 65,000 kw., and that on the other line is about 2 per cent with a maximum load of about 4000 kw. The generators are of about 10,000 kw. each. It is desired to give constant voltage at both substations, and as it is necessary to parallel the two systems at various times during the day, to make full use of the generating capacity, the voltage disturbances were very objectionable. However, by making use of bus reactance, which has already been installed, it is possible to operate these stations in parallel at any time, each system getting its proper voltage regulation.

This is a point which may not be of particular value in city distribution work, but may be well to keep in mind in connection with the operation of more extended transmission systems.

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OUTDOOR VS. INDOOR SUBSTATIONS

BY ALEXANDER MACOMBER

ABSTRACT OF PAPER

The development of the outdoor substation vs. the indoor type is an interesting commentary on the adaptability of engineering progress to new fields and the subject is briefly recapitulated in this paper, in line with the developments and application of this branch of transmission work.

The causes for development of this apparatus, together with a general description of the classes of apparatus involved which have been changed to meet new conditions, are given. The application of the indoor vs. the outdoor substation to services of different character is indicated, and the tendencies for the future briefly touched upon. A comparison of the advantages and disadvantages of the types considered is outlined.

In general, it appears that the equipment for outdoor installations has been successfully developed to meet the severe conditions imposed, and the numerous installations involving outdoor features indicate the extensive use of this idea in the future, while its development as applied to the central station itself affords a considerable field for attention.

THE DEVELOPMENT, in the last half-dozen years, of the outdoor substation vs. the indoor type, with its attendant problems, is a most interesting commentary on the adaptability of engineering progress to new fields. Primarily, as in most such cases, the cause was an economic one, the desire to serve from transmission systems the small consumer who could not be reached on account of the excessive first costs of installation.

The development of suitable apparatus to meet this fundamental condition has opened up a new field for substation development, and progress along engineering lines necessitated by new and peculiar conditions has indeed been remarkable. These problems, especially in reference to the class of work which introduced them, have been well solved, but the possibilities in application to larger and broader fields has meant attacking problems of a far more complex nature. The success obtained justifies the expectation that outdoor substations will occupy a very important position in the development of transmission work. The extent, however, to which it is desirable to develop these propositions, must receive serious consideration dependent

on the engineering features of design and operation, and fundamentally on the economics of the problem.

This matter has been ably discussed previously, but its importance is such that it is proposed briefly to recapitulate the subject in view of its developments and possible applications, trusting that discussion of practical experience will be afforded.

Development of Equipment

To meet the engineering conditions of outdoor operation, considerable experimental work has of course been necessary, and results indicate that there is nothing inherent in the requirements of apparatus for these conditions which apparently cannot be successfully met.

The classes of apparatus involved which have required development to meet new conditions may in general be grouped under (1) protective equipment, (2) transformers, and (3) control equipment.

Protective Equipment

The most important protective apparatus affected by outdoor installation is the electrolytic lightning arrester, which offers the most complete protection available at present for high-tension lines. Heretofore it has been necessary to protect this equipment by housing, but the development of low-temperature electrolyte, together with other details of design, makes it now feasible to place the entire equipment out of doors, even under the most severe climatic conditions. The winter season when the severest temperatures are encountered, is also, as a rule, free from lightning disturbances, though it is important to secure continuous service of protective devices of this nature on account of surges occurring on the lines, the necessity being particularly noted where the switching of the high-tension systems is liable to cause serious line disturbances and consequent breakdowns at weak points. It is as much the function of the arrester to absorb these disturbances as to avert the direct effects of lightning itself.

Transformers

The operation of outdoor transformers is no longer experimental. The principal difficulty to be met is the climate, with its changes in temperature and atmospheric conditions. In general the outdoor type of transformer is similar to the indoor type except that the cover and leads are designed to shed moisture and provide the necessary higher factors of safety.

Both self-cooled and water-cooled transformers are applicable to this service, with due consideration of its requirements. In the former case, grades of oil suited to the conditions are of course necessary, the only serious difficulty being on account of possible freezing. As a rule the load of the transformers will keep the oil sufficiently warm, but it is important that precautions be taken in order to prevent condensation of moisture. If necessary this is accomplished by small heating coils installed in the tops of the transformers. The freezing of the oil itself in idle units or under severe conditions may also be guarded against by the installation of external heating devices under the casings.

This freezing of the oil may be serious, particularly if transformers are out of service, because on energizing them, dissipation of heat, with the oil frozen, is liable to be slow, and inasmuch as the temperature rise in large units is about 20 deg. cent., the windings might be injured before the oil is liquefied. Little trouble is experienced, however, as ordinarily oil will not freeze at a temperature above −15 deg. cent., and special grades solidify at a considerably lower point.

The use of water-cooled transformers involves similar precautions against moisture, with the addition of suitable protection to the water circulating system, although the water of itself, by its circulation through the transformers, would not freeze except under severest conditions, provided the external connections are properly protected.

There apparently has not been much experience with air-blast transformers out of doors and it would seem that there might be a field for them as they do not offer the difficulties in giving climatic protection which are encountered with other types of transformers, provided moisture is kept out; and the cost would be less.

Control Apparatus

The design of control apparatus, such as switches, circuit breakers, etc., has also met the severe conditions imposed, and outdoor switches of extremely high voltage are operating satisfactorily in severe sleet and snow storms. As with the other apparatus, the general indoor types have been made suitable for outdoor service by perfection of details, such as enclosing the mechanisms, motor control, etc.

In general, then, it may be fairly stated that the use of the outdoor substation is not to be limited particularly by the lack of apparatus suitable for the severe operating conditions, and

it is certain that even greater steps in the improvement of apparatus of this nature will occur.

Application

The indoor substation has been highly developed to meet the various classes of service imposed upon it, and in fact has become very nearly standardized. It is hardly necessary to consider its development and status here, except as a comparison with those particular classes of service in which the outdoor substation may appear as its competitor, the advisability of the latter depending on a careful consideration of the various advantages and disadvantages as compared with the established type of indoor substation.

Generally speaking, for the purposes of considering outdoor installations, substations may be classified as serving the requirements of (a) small isolated loads, (b) large capacity loads, and (c) apparatus auxiliary to central stations.

A brief discussion of these respective divisions will indicate some of the requirements and opportunities incidental to each.

Small Isolated Loads

It was in the class of small isolated loads that the development of the outdoor substation first started, and this has afforded its greatest field to date.

Complete outdoor installations up to a few hundred kv-a. have enabled service to be given to isolated customers and small communities which otherwise could not be profitably served directly off the main transmission lines. It is possible to locate such substations almost anywhere, the structural and foundation requirements varying with conditions. The simplicity of design and construction has meant a small investment and a minimum of operating troubles. High-tension switching is usually limited to air-break types, instead of the costly oil switches, while lightning protection is afforded either by the electrolytic lightning arrester or the cruder horn type. Most such installations have been free from elaborate secondary control, that provided being, if any, of the simplest type, established in weatherproof housings. There can be hardly any question as to opportunities for this type of station, and its rapid adoption and extending installation, on account of the factors of simplicity, low cost and lack of attendance, indicate the importance of its field.

Large Capacity Loads

The application of the outdoor substation to large capacity installations, particularly where the secondary control is split up into various circuits with more or less auxiliary apparatus, confronts us with larger problems. The substation may combine not only the functions of a switching station, but also that of supplying a large load to a community, and in general its location would not be affected by the type adopted, provided sufficient space is available.

With substations of this character, involving attendance, it is necessary to provide a suitable building designed for at least part of the installation. What part of the high-tension apparatus may properly be installed out of doors depends largely on the saving thereby effected. The actual outdoor apparatus must be provided for separately, and a combination of the indoor and outdoor substation will in many cases prove most advantageous. In some cases it is feasible to place the whole outfit out of doors, including the low-tension control equipment, provided the latter is not extensive, but in most cases it is questionable whether the operating features will permit this extreme. In cases where attendance is required it is certainly advisable to install the secondary equipment indoors.

The manner of installing the outdoor equipment will, of course, depend upon the size and importance of the layout. In general the incoming and outgoing lines must have proper terminal structures for connection and distribution to the banks of transformers. The transformers themselves should be provided with proper foundations, preferably of concrete, so designed that they may be removed on rails, and provision should be made for heating the cases if climatic conditions require it, while the piping for oil or water must be carefully considered.

The installation of lightning and control equipment is also subject, in general, to the same requirements.

A most important detail of the outdoor installation is that of providing proper facilities for repairing damaged apparatus, and large stations must provide some shelter where such repairs can properly be made.

The space occupied by the outdoor installation will, of course, be large, and adequate provision must be made for preventing anyone from coming in contact with the equipment.

Apparatus Auxiliary to Central Stations

Many central stations operated in connection with transmission systems have a considerable portion of their buildings given up to high-tension equipment and apparatus incidental to its operation.

The outdoor installation of such latter equipment would, in many cases, reduce the building cost materially, provided the extra outdoor space is available. The features of installation would be similar to those noted above. This phase of outdoor application is worthy of considerable attention and study.

Comparisons

Considered generally, the following are the advantages and disadvantages of outdoor installations:

Advantages	Disadvantages
Lower first cost	Repairs
Ease of extensions	Operating risks
Reduction of fire hazard	Danger to public
Simplicity of layout	Appearance.

Reduction in cost was the cause for the development of this type of construction, is the reason for its continuance, and will govern its extensive application, when properly interpreted. For the small isolated substation of a few hundred kv-a., the cost will be from 25 per cent to over 50 per cent cheaper than the corresponding indoor station. For large installations, particularly where a building is provided for secondary control, the per cent of saving is much smaller, the less being the cost of the outdoor part of the installation in proportion to the total, the less being the saving due to this construction.

In connection with the cost, reduction of fire risk is important and outdoor service reduces this to a minimum.

The simplicity of either complete or partial outdoor installation is particularly attractive. With the intensive development of the indoor station we have succeeded in obtaining about all the elaborateness of design possible, and any development offering opportunity for simplicity of construction and operation should be welcome.

The disadvantages outlined have been mentioned generally in passing. The most serious ones are those of operation and facility for repairs. Experience indicates that operating difficulties are well overcome, and generally speaking, damage to modern apparatus is reasonably rare. Danger to outsiders can

certainly be prevented by fencing, etc., while the matter of appearance is only of interest in certain localities.

Summary

Summarizing the situation, we find that the equipment for outdoor installations has been developed to meet the severe conditions imposed. Successful operation of installations of this character during several years shows that operating difficulties are unusual.

It is significant that at present there is installed, or under construction, approximately 300,000 kv-a. in high-tension outdoor type transformers. The query may well become, instead of "when shall we use the outdoor substation?" rather "when shall it *not* be used?" The cost is the main factor, although operating features with increasing high voltage become attractive on account of the simplicity of the layout and the tendency to make the high-tension equipment a part of the line itself.

The development of these ideas when applied to the central station itself should be as marked as it has been in the case of the substation, although the limits desirable to impose must in all cases be determined by the particular problem under consideration.

Presented at the 2d Midwinter Convention of the American Institute of Electrical Engineers, New York, February 25, 1914, under the auspices of the Electric Power Committee.

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OUTDOOR SUBSTATIONS IN NEW ENGLAND

BY FRED L. HUNT

ABSTRACT OF PAPER

The present development of outdoor switching apparatus and transformers for systems of 110,000 volts or less is such as to make their use entirely successful, and in most transformer substations, a considerable saving in first cost can be accomplished without increase in operating expenses, by making use of this type of equipment.

This paper gives a brief description of two substations of 10,000 kv-a. ultimate capacity, just put into operation, in which all the high-tension switching apparatus (66,000 volts) and the transformers are outdoors. The low-tension apparatus (13,200 volts) and the railway apparatus are indoors. This arrangement is based on the three following principles which have in this case proved to be sound:

1. That the greatest saving in building cost can be made by putting all high-tension work outdoors.
2. That the switching apparatus, lightning arresters and transformers of voltages in the neighborhood of 66,000 volts are practical and may be successfully operated outdoors in New England.
3. That distributing switchboard, control switchboard and railway apparatus and switchboard are not suitable for outdoors.

DURING the past summer, there have been built and put into operation by the Amherst Power Company two substations, a brief description of which may be of interest in connection with the present tendency towards the use of outdoor substations. One of these is located at Chicopee and one at Agawam, Mass., both being supplied from the company's double-circuit, 60-cycle, three-phase, 66,000-volt transmission line extending from Turners Falls to Springfield. The accompanying illustrations show various views of these substations, which are practically duplicates as far as general layout is concerned.

When these stations were being laid out, considerable attention was given to a study of the advantages and disadvantages of indoor and outdoor apparatus, the result of which was the adoption of what might be called a semi-outdoor substation in which all the 66,000-volt equipment, including the step-down transformers, was placed outdoors, as were also the aluminum lightning arresters on the 13,200-volt outgoing lines, while the

13,200-volt buses and switching, the control switchboard, the 2300-volt distributing switchboard and the railway apparatus were placed inside.

The choice between indoor and outdoor apparatus in different parts of the equipment was based on the following considerations:

1. The 66,000-volt apparatus was the most bulky part of the equipment, and therefore the greatest saving in building space could be accomplished by putting it outdoors.

2. The more complicated switching necessary with the numerous 13,200-volt and 2300-volt outgoing circuits and synchronous motor circuits would have been much more difficult and expensive to handle in an outdoor installation. Hence, they were placed inside.

3. The control switchboards, with their metors, instruments and storage battery, and the railway motor-generator sets, have not at the present time been developed to the point where it is practical to operate them outdoors; therefore these were placed inside. Except in the case of the switchboards with their meters and instruments, the storage battery and the railway sets, none of which are suited to outdoor operation, the relative location of the remainder of the apparatus, that is, whether it would be placed indoors or outdoors, was determined principally by comparison of estimated first costs, since no well-founded objection to the use of outdoor aluminum lightning arresters, oil switches, transformers or buses could be found.

The saving in the first cost of the building may be arrived at very closely on the basis that the cost of two proposed buildings, erected on the same site, for the same purpose and of the same general design and material, will, within reasonable limits, have first cost in the direct proportion to their cubic contents. A building, similar to the one actually erected, but of the dimensions necessary to accommodate indoors all the apparatus, including the 66,000-volt equipment, allowing for the same switching scheme, and providing a space for future expansion equal to that which is incorporated in the present station and outdoor foundations, would cost on the above basis 202/86ths of the cost of the present building. After allowing for the extra cost of outdoor apparatus and the cost of outdoor foundations and steel structures, the saving in this case was an amount equal to 11 per cent of the cost of the complete station and equipment as built.

The general arrangement at the Chicopee substation (see

Figs. 1 and 5) is as follows: A tap circuit is brought in from each of the two transmission lines through choke coils, disconnecting switches, and solenoid-operated non-automatic oil switches to a transfer bus, from which the transformers are supplied through disconnecting switches and solenoid-operated automatic oil switches, one set for each bank. An aluminum lightning arrester is installed on each incoming line. At present there is one bank of three 1500-kw. oil-cooled transformers of the radiator type in use here, with one spare unit, and foundations and conduits are installed for a second bank. This type of transformer construction brings the cost of oil-cooled transformers for outdoor work down to a point where their increased cost over water-cooled transformers is so little that it does not pay to add the complication of water cooling for the small saving in first cost that can be accomplished, especially where the water would have to be pumped, as in this case, and where, as in all outdoor stations in the northern part of this country, special precaution must be taken to prevent the freezing of water pipes. From the transformer bank one circuit is carried underground into the building to the 13,200-volt double bus in a concrete bus structure.

The arrangement so far as outdoor station is concerned, is the same at Agawam (see Fig. 2) except that there is a difference in the capacity of transformers, and there are two circuits from the secondary side of the transformers into the building; one leading to the 13,200-volt bus, and one to the 2300-volt bus, as power is distributed at both voltages from Agawam station.

Attention may now be called to some special features of the outdoor equipment. The oil in the outdoor transformers freezes at −15 deg. cent. It is therefore necessary to keep the temperature of the oil in the spare transformer above this point if it is to be ready for immediate service. This will be accomplished by connecting the spare transformer to the bus on the low tension side, from about Jan. 1st to Mar. 10th of each year. During the remainder of the year the temperature of the oil in the spare transformer does not go down to its freezing point when left without artificial heat.

The transformers and oil switches are connected by a complete piping system to a two-compartment oil tank buried in the ground, so that oil can be drained from any transformer or oil switch into its respective compartment of the oil tank,

and from there can be pumped through a portable oil filter press back into the transformers or switches. Alarm thermometers on the transformers are connected to bells in the station. There is installed in the cover of each transformer a small heating unit taking 200 watts at 110 volts. The object of this unit is to keep the air in the top of the transformer, and especially the spare transformer when not excited, a little above the temperature of the air outside, so that in the process of breathing, which is sure to be present to some extent in any large transformer subjected to varying temperatures, the air taken in, even though heavily laden with moisture, will have that moisture vaporized by coming in contact with the warmer air inside, rather than being further condensed by coming in contact with cooler air inside, which latter condition would occur if there was no artificial heat inside the cover of the transformer.

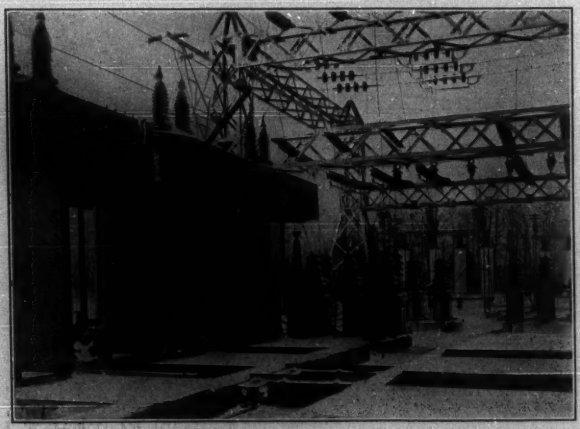
When it becomes necessary to disassemble a transformer it is rolled on to a transfer truck upon which it is run into a compartment at one end of the station where a hoist is available of sufficient capacity to lift and remove the core. Switch hooks used for operating the disconnecting switches outdoors are fitted with a copper cone at about the middle of the handle, which cone is grounded when the hook is to be used. All the outdoor aluminum lightning arrester cans are painted white to overcome a difficulty experienced in warm climates where the absorption of the sun's heat by dark-colored cans has raised the temperature of the electrolyte of the arrester to a point where it was damaged. Two coats of white paint on these cans have been sufficient to keep the temperature of the arresters below the danger point in these installations, up to the present time. This same treatment may be applied with similar results to the transformers where excessive temperatures are reached on account of the sun's direct rays.

The winter weather test of these substations has already begun and the results so far observed are satisfactory. The Chicopee station after a recent sleet storm is illustrated in Fig. 3.

Each outdoor station is surrounded by an iron picket fence and all the equipment is set on concrete foundations extending below frost line and about 15 in. (38.1 cm.) above the final level of the ground. Thus far in the operation of these stations nothing has occurred which indicates any important point of disadvantage in the outdoor arrangement, except that some difficulty was at first experienced in keeping the joints of the

FIG. 1—GENERAL VIEW—CHICOPEE SUBSTATION. [HUNT]

FIG. 2—GENERAL VIEW—AGAWAM SUBSTATION. [HUNT]



[HUNT]

FIG. 3—OUTDOOR APPARATUS CHICOPEE SUBSTATION.

[HUNT]

FIG. 4—OUTDOOR SUBSTATION AT CONSUMER'S PLANT—750-KV-A. TRANSFORMER BANK, 13,200 VOLTS TO 2300 VOLTS.

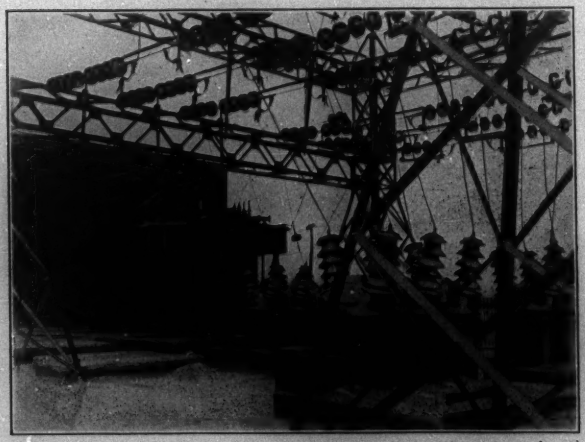


FIG. 5—CHICOPEE SUBSTATION AFTER SLEET STORM. [HUNT]

cooling radiators on the transformers oil-tight, due to the wide range in temperature to which they were subjected every 24 hours. The design of these radiators has now been changed, and the new radiators have thus far stood the test of wide temperature changes without developing leaks.

It is probable that in practically all substations of the same general arrangement as these, considerable saving can be accomplished by the outdoor arrangement of the high-tension apparatus, except where cost of land is very high, as in cities. There is no reason why, with proper local conditions, a considerable saving cannot be accomplished by the use of outdoor apparatus at generating stations. In other cases, the saving may be small or none when the particular arrangement of canal intakes and generator rooms is such that only a small additional expense is required to house the transformers and high-tension switching. Each case should receive special consideration. There appears to be no good reason for using outdoor apparatus except where a saving in first cost can be shown.

Outdoor apparatus is also used on this system at several of the consumers' substations, where power is delivered at 13,200 volts and stepped down to 2300, 550, 440 or other voltages. Fig. 4 is a view of a typical station of this kind where power is delivered at 13,200 volts to a bank of three 250-kv-a. oil-cooled, single-phase transformers, and stepped down to 2300 volts for use in a textile mill.

The transformers are connected to the 13,200-volt circuit through combination horn-gap arresters and choke coils, and horn-gap disconnecting switches, and the power is metered at 13,200 volts by the use of outdoor potential transformers, indoor current transformers under shelter, and a meter in a box with glass cover. The tower stands approximately 20 ft. (6 m.) high, the bottom of the transformers being about 10 ft. (3 m.) from the ground.

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INDOOR AND OUTDOOR SUBSTATIONS IN PENNSYLVANIA

BY H. L. FULLERTON

ABSTRACT OF PAPER

This paper covers some points in substation design for installations for the lower voltages, including choice of location, type of building and arrangement of electrical apparatus.

The subject is treated in three divisions, namely: customers' substations fed from the distribution system, customers' substations fed from the transmission system and company's substations. Attention is called to some of the advantages of both the outdoor and indoor substations for each of the different divisions.

Points to be considered in the selection of locations for substations are outlined and several types of buildings, particularly the one of concrete slab construction, are described. Attention is also called to different arrangements of electrical equipments, which may be employed for installations of various sizes.

Different schemes for installing high-tension switchboard apparatus are considered, attention being called to the open wire and the cell structure installations, with special reference to the concrete cell structure and the method employed in its construction.

THE OBJECT of this paper is to cover in a general way outdoor and indoor substations of voltages up to and including 20,000, the limit being drawn at 20,000 volts because, where a higher transmission voltage than this is used, it is necessary to transform to a lower voltage on entering centers of population. I intend to call attention to some of the main points to be considered in determining the best location for substations for various purposes, to show some forms of substation buildings which can be used under various conditions, to give some of the advantages of the outdoor and indoor types, and to show some forms of electrical installations which have been used to meet the various conditions which present themselves in substation design.

For convenience in handling the subject, I shall divide it into two general divisions:

1. Customers' substations, or those which are installed on

the customer's premises and used only for feeding his service. This will be subdivided into:

(a) Those fed from the regular distribution system.

(b) Those fed from the transmission system.

2. Company's substations, or those which are installed by the company at a center of load and used to deliver service at a reduced voltage to the consumers within that district.

Customers' Substations Fed from Distribution System

Unless the customer is along the line of a low-tension distribution system, it is necessary to install a substation to serve him with low-voltage service. This substation may be of any size from a small transformer on a pole on the street, to a large capacity installation in a regular substation room, depending on the customer's load. The probable demand of the customer determines the type of substation to be installed, and whether it be fed from the primary distribution mains at a medium voltage or from the transmission system direct, at the higher voltage. It is impossible to handle some of the larger installations economically from the primary distribution system, which is usually between 2000 and 5000 volts.

Customers whose demands are small, are ordinarily served by installing a small transformer on a pole adjacent to their load. This installation is very simple and serves quite well, until the demand requires transformers which are too large to be conveniently handled in this manner, but 50 kw. is probably about the limit for this type of construction. When the demand is above this point, it is necessary to make some special arrangement to furnish his service. If the location is such that room can be secured on the customer's premises, the transformers can be nicely installed on ordinary wooden poles something after the manner shown in Fig. 1.

In this arrangement two poles are placed on 10-ft. (3-m.) centers and a platform built between poles. A very neat arrangement can be made of the wiring on both the primary and the secondary side and the construction can be made safe both mechanically and electrically. The platform is constructed by fastening a channel to each side of the pole by through bolts and building thereon a wooden floor. The limit for an installation of this kind is about three 50-kw. transformers.

Where greater capacity is required, it is often possible to set the transformers on a platform on the ground, enclosing them

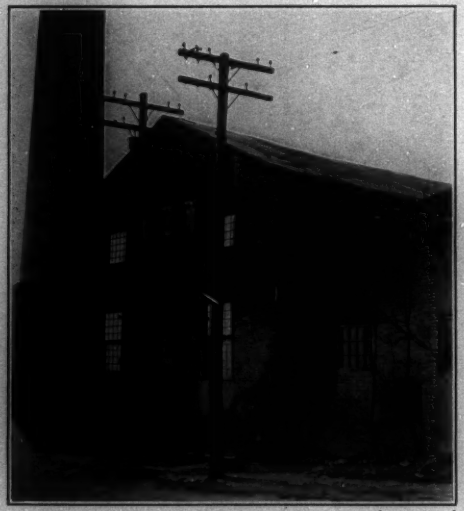

FIG. 1 [FULLERTON]

FIG. 2 [FULLERTON]

FIG. 3 [FULLERTON]

FIG. 4 [FULLERTON]

with a high fence, so as to guard against persons coming in contact with electrical apparatus.

If conditions are such that an outside location cannot be secured for the transformers, it is then necessary to procure an inside location and build a transformer vault or indoor substation. Of course, the customer wants the transformers located in the space that cannot be used for any other purpose, which is usually in the basement or sub-basement, and below the sewer level, while the rules of the National Board of Fire Underwriters require transformer vaults to be sewered, also ventilated to the outside air. It quite frequently happens that the building is nearly completed before the architect remembers that a transformer vault will be necessary, unless some representative of the operating company impresses very forcibly upon him the necessity of making provisions for the same. Then the only available location is in some out of the way corner, where the transformers must be taken in through important parts of the building, often down flights of stairs of costly construction and entirely unsuited for the passage of heavy apparatus. When a freight elevator is installed, it is usually so located that it is not available for handling the substation equipment.

If the architect has provided a transformer vault, it is usually about one-half the size that is necessary. In one particular instance that I recollect, the installed transformer capacity amounted to 1125 kw., while the space provided by the architect was 3 by 10 ft. (0.9 by 3 m.), in which he expected us to place both the transformers and switching apparatus. In case no vault has been provided, it is necessary for the operating company to make the installation, which must be made in accordance with the rules of the National Board of Fire Underwriters, hence, it is necessary for the company to construct its own transformer vault.

Fig. 2 shows a fireproof transformer vault which has been installed in a building in which the architect had failed to make provision for the transformers. This type of vault has given very good results, where used, and is quite pleasing in appearance and cheap and easy to construct. The vault is built up of concrete slabs 3 by 6 ft. (0.9 by 1.8 m.) and 2 in. (5 cm.) thick, and an iron door having similar dimensions. The slabs and the doors can be prepared in the shop at odd times and kept in stock for such cases. Two or three men can easily handle

these slabs and erect the transformer vault in a short time. A vault of this type of construction can be made in any size from 3 ft. by 3 ft. (0.9 by 0.9 m.) and 6 ft. (1.8 m.) high, up, in multiples of three. It is portable, being simply held together at the corners by small angles and can readily be moved in case any change is being made which requires its removal. The bolt holes, etc., in the slabs are cast in at the time of preparation. As will be noticed from Fig. 2, this construction furnishes a convenient place for mounting oil switches, instruments, etc., so that the customer can operate his installation without going near the high-voltage apparatus. Neither is the meter reader in any danger of coming in contact with high-voltage wires, when making his monthly calls.

When the customer builds his own transformer vault, which is usually of brick or terra cotta construction, it is often possible to have him build in the wall a slate slab to allow of the mounting of the switches and watt-hour meters in a manner similar to that shown in Fig. 2. The back of the slab should be mounted flush with the inside of the wall. Where the slab is mounted in a 13-in. (33-cm.) brick partition, the switch handles and instruments are well protected by the surrounding walls.

Location of Transformers. The following points should be observed in selecting a location for the transformers:

1. Position of customer's load.
2. Location of operating company's street mains.
3. Accessibility for delivering material.
4. Accessibility for operating company's employes.
5. Possibilities of ventilation and sewer connection.

In the selection of a location from the electrical viewpoint, the transformers should be installed as near as possible to the center of the customer's load, as this will give him the least investment in copper and the best regulation to his various tablet boards. The company's street mains should also be considered. It is very desirable, since the connection is usually made with underground cable, to have as short and straight a run for the cable as is possible.

The location of the transformer vault should be such that the material can be delivered with as little work inside the customer's building as is possible. It should also be such that the company's employes can have access at any hour of the day or night, in case of trouble on the system. Delays caused by inability to find watchmen or building superintendents are often

quite serious. Since ventilation and sewer connections are required, it is necessary that this be taken into account in determining the vault location and a position should be selected that will lend itself to these requirements.

Comparison of Outdoor and Indoor Installations. Some of the advantages of the outdoor installations are:

1. Less cost for making installation.
2. Usually more accessible for company's employes in case of trouble.
3. Less difficulty in connection to company's lines.
4. No transformer vault required.
5. Better ventilation.

Some of the advantages of indoor installations are:

1. Apparatus more accessible for inspection or repairs.
2. Less danger of unauthorized persons interfering with apparatus.
3. Customer can have control of the installation on the primary side, by means of oil switches, if desirable.
4. Apparatus protected from weather.

Customers' Substations Fed from Transmission System

When the demand of the customer is so great that he cannot be fed from the regular distribution system, it becomes necessary to install on his premises a substation to serve him from the transmission system, which may be of any voltage from 5000 up. Where space can be secured on the customer's property, it is often possible to supply him with service from an outdoor substation, installing switches, lightning arresters, fuses, etc., on poles and locating the transformers on a platform, on the ground, or on a suitable structural iron tower some feet above the ground.

Fig. 3 shows a 200-kw. outdoor installation in which the transformer is installed on a concrete foundation between two poles, on which are mounted the pole top switches, fuses, lightning arresters, etc., and around which is built a high picket fence with a couple of strands of barbed wire above the top of the pickets. Entrance is gained to the enclosure through a gate, which is kept locked. This is about as inexpensive an installation as it is possible to make and yet it has very satisfactorily furnished service to this brickyard for several years. The picket fence and barbed wires are even a better protection to the installation than mounting off the ground on towers,

as shown in Fig. 4. Boys are not so apt to climb the picket fence as they are to climb the towers.

Fig. 4 shows an installation in which the transformers are mounted some ten or twelve feet above the ground on a structural steel construction, the top of the tower, like the poles in the previous case, being used for mounting the switching apparatus. This makes a very good arrangement up to the point where the transformers become too large to be handled readily.

Where it is not possible to secure outdoor space or when objection is made to the outdoor installation, the apparatus must be installed in a building either erected for the particular purpose or in one that is already constructed and can be used for the installation. Where the power is to be supplied to machines in a large factory, it is often desirable to enclose a small space for substation purposes in the building near the center of the load.

Fig. 5 shows the inside view of a substation erected in the center of a large screw and bolt works. The building is of steel and corrugated iron construction. The high-tension service is brought to the substation through cables supported from the roof of the building. By this arrangement, the substation was located near the center of the load and not only saved the customer considerable on his copper investment, but gave him good regulation to his motors, which would have been impossible with the substation located at one end of the factory, at a point which he had selected and at which point he was very determined the installation should be made. This customer is served with two high-tension lines, his running load being approximately 1000 kw. Three 375-kw., single-phase transformers controlled by automatic oil circuit breakers are used. The transformers are connected to the bus on both the high- and low-tension sides by disconnecting switches, thus enabling any one transformer to be cut out for either inspection or repairs without interrupting service. The customer's switchboard and motor-generator set are located in one end of the substation building.

In another case, where a substation was built in the center of a large steel mill, it so happened that the works were built on either side of a street, so it was possible to locate the substation in a very accessible point and still keep to the center of load. The substation was designed so that it would be able

to handle the entire power requirements of the mill. When the installation was first made the demand was only about 400 kw., but they have been steadily increasing their demand until they now have connected about 2500 horse power and are making inquiries for more. Hence is emphasized the necessity for designing substations so that additions can be made from time to time as the customer's demand increases.

It is usually quite difficult to make the customer see that he should allow ample space in his substation, so that increase in size of apparatus can be made as his demand requires. Usually he thinks that his demand will be small and that you are requiring him to give up space much too large for your purposes.

Where the customer's demand is of any considerable size it has been found quite desirable to install check meters on his service, the average of the two meters being taken as his consumption. When there is a difference of about 2 per cent in their readings, the meters are recalibrated.

The following points should be observed in selecting locations for and in designing customers' substations:

1. The installation should be as near as possible to the center of the customer's load.

2. The installation should be at a point where it will be least in the customer's way, and still be accessible to the operating company.

3. If outdoors, the installation should be well enclosed, so as to prevent unauthorized persons from getting into danger.

4. The design should be such that additions and repairs can be made to the equipment with the least possible interruption to the customer's service.

5. The design of the building should be such as to allow of the ready changing of transformers as demand requires.

6. The source of power should be such as to give him the most reliable conditions of service. Customers who are vitally effected by outages should be furnished with emergency service.

7. Apparatus should be so arranged that the customer can handle his own switching at the direction of the operating company.

8. Installation should be made as well insulated and as nearly fool-proof as possible, since it is usually operated by men unfamiliar with high-tension current.

Comparison of Outdoor and Indoor Installations. In customers' substations the field for the outdoor installations seems to be with the smaller isolated customer, where he has vacant space about his plant. Where the larger installations are made, the outdoor type does not seem so well adapted.

Some of the advantages of outdoor installations are:

1. No cost for new buildings.
2. No space required in customer's present buildings.
3. All high-tension current kept outside of customer's buildings.

Some of the advantages of indoor installations are:

1. More reliable switching equipment can be installed.
2. Better facilities for inspection and repair.
3. Apparatus protected from weather.
4. Switching can be handled more easily by customer.
5. Less danger of accident to public.
6. Safer arrangement of apparatus possible.

Company's Substations

Where the operating company generates its power at a large central station, which is usually at a point quite remote from the demand, or where it purchases power from some transmission company, it is necessary for it to receive current at a much higher voltage than that at which it can distribute to the small light and power consumers, hence, it is obliged to install a substation to transform the power from the transmission voltage to a lower distributing voltage. The size of this substation, of course, depends upon the character of the district to be served, which may be anything from a small suburban town, having a small demand, to the thickly populated power district having several thousand kilowatts demand.

When it has been decided that the time is ripe for a substation in a certain district, one of the most important and by no means the easiest problem is the selection of a location. Some of the points which should be considered in making a selection are:

1. Location of the present load.
2. Future development of the district.
3. Distance from existing substations on the system.
4. Outlet from the substation for the various feeders.
5. Street frontage.

The above points determine the geographical location for the substation in the district. It is not always best to locate

FIG. 5 [FULLERTON]

FIG. 6 [FULLERTON]

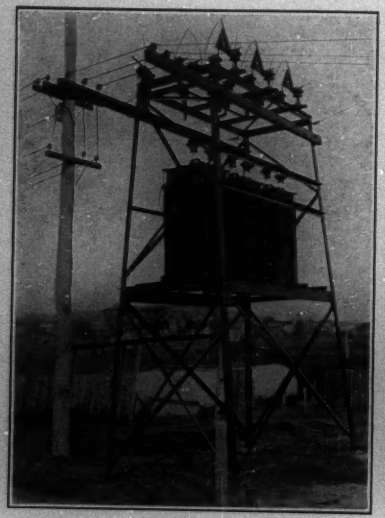

FIG. 7 [FULLERTON]

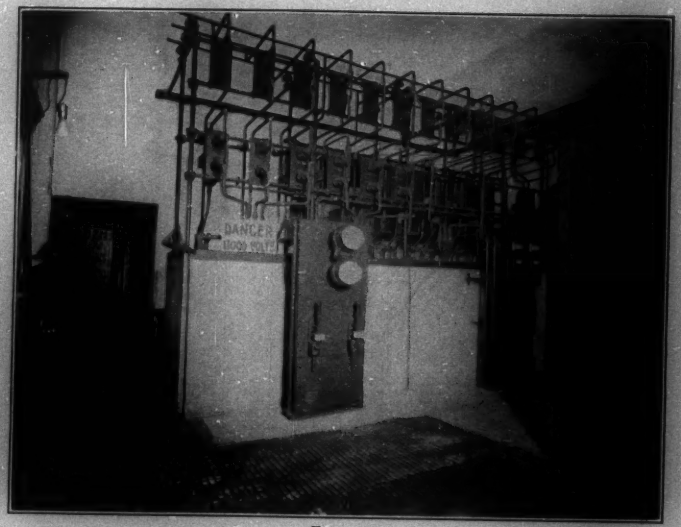

FIG. 8 [FULLERTON]

in the center of the existing load, as the tendency may be toward development in one particular direction due to natural conditions in this section. Again, the demand may be too close to an existing substation to warrant a second one, therefore, it may be advisable to locate to one side of the present load, and be in a better position to handle the growth outward from the present substations.

The outlet from the substation should be given considerable attention; if aerial lines are to be installed, a location such that it is possible to feed in at least two directions should be selected, and a corner lot would be preferable, where the lines could radiate from the substation in four directions. This means that the pole line from the substation will not be so heavily loaded as if only one outlet were available. Even though it be an underground district, it is quite desirable to have several outlets and save congestion in subways.

Substation Buildings.—Probably one of the least expensive buildings suitable for substation purposes is that made of structural steel and corrugated iron, but while this building is comparatively low in cost, its life is also comparatively short, and on the whole it is not very desirable.

A type of building, which compares very favorably in cost with one of steel and corrugated iron, but which has much greater life, is shown in Fig. 6. This building is simply an enlargement of the slab transformer vault construction referred to earlier in this paper. It is built up of structural steel on which are bolted two-in. (5-cm.) reinforced concrete slabs of standard size; the roof is also made of these slabs, supported by the framework of the building. The concrete roof is covered by a tar paper and gravel roofing. About a six-in. (15.2 cm.) slope to the 12-ft. (3.6 m.) width is allowed. Steel sash, wire-glass windows and steel louvres are used. For air supply, a section of concrete is left off one or two of the lower slabs, leaving the expanded metal reinforcing exposed. This allows a free inlet of air and at the same time prevents large objects from entering. Regular 1½-in. (3.8 cm.) expanded metal is used in the construction of the slabs.

This building compares very favorably in appearance with that of the average garage or out-building which may be found on back streets or alleys, and makes a fireproof construction. It is also portable and can be used to good advantage at a location from which its removal at some future time may be

desired. This building is 12 by 18 ft. (3.6 by 5.4 m.) and 15 ft. (4.5 m.) high. In it are installed three 250-kw. transformers serving four 2200-volt feeders.

Where a better type of building is required, brick or stone is usually used in the construction and as elaborate a design as is desired can be utilized. By the use of rock faced brick and sawed stone, a building very pleasing in appearance can be constructed at a reasonable cost.

The cost of buildings, or their equivalents, for substation purposes varies so widely, due to location and cost of labor, that it is impossible to give an estimate that would meet all conditions; however, I am giving a relative value to the various types, taking as a unit the least expensive installation—that with the outdoor apparatus installed on a concrete platform and enclosed by a fence.

Concrete foundations, poles, picket fence	(Fig. 3.)	1.00
Structural steel tower	(Fig. 4.)	2.25
Steel and corrugated iron building (12 by 18 ft)		4.50
Steel and concrete slab building	" " "	6.75
Ordinary red brick building	" " "	15.00
Rock faced brick and sawed stone	" " "	25.00

Substation Installations. Like the buildings, the electrical installation has a very wide range of possible combinations. The outdoor substation is the cheapest, especially where no switching or regulating apparatus is required. However, it does not seem particularly well suited for installations where there is small apparatus such as instruments, oil switches, feeder regulators, etc., which should be housed. Of course, it would be possible to put the transformers and high-tension apparatus on the outside, erecting a building for the housing of the low-tension apparatus. Installations of this type have been made and work out very nicely for the small demands, but the present designs for outdoor switching apparatus for 10,000 and 20,000 volts are not such as to allow of very large installations being made along these lines.

It frequently happens that a transmission line may pass by a small hamlet or power customer from which a small revenue can be procured and still the income will not justify making a very expensive substation installation. This class of business can be taken care of by an outdoor substation. By an installation of this kind the town is furnished with electric light, which it may very much desire, and the operating company receives a small revenue from a district which would not allow

of the installation of a regular substation building and apparatus. Fig. 7 shows an installation of this type. The transformers are mounted on a tower construction some feet above the ground. Pole top switches, fuses, etc., are used, no regulators or switches being installed on the low-tension side. If regulators are necessary, the outdoor pole type can be used.

Diagram *A*, Fig. 15, shows the wiring of this installation. The apparatus is connected to the transmission line through a switch and fuse, a choke coil and ground horn being inserted between the switch and fuse.

Diagram *C* shows the wiring of the installation made in the concrete slab building shown in Fig. 6. The transformers are protected by high-tension fused circuit breakers which also act as disconnecting switches for the incoming transmission lines, the transformers being connected directly to the high-tension bus. On the low-tension side each circuit is controlled by an oil switch and fuse. Lightning arresters are mounted on the poles outside the building.

Neither of the above installations can really be said to have a high-tension switchboard. This is scarcely necessary where the substation is small and is fed by only one or two transmission lines. Where the substation is important enough to have feeders from separate power houses, or where it is used as a switching station for high-tension lines, it is necessary to install some type of high-tension switchboard.

The simplest and probably the cheapest installation that can really be called a switchboard is the open wire type. Fig. 8 shows a fair example of this type of construction. The oil switches are mounted in concrete cells, while the busbars, disconnecting switches, etc., are mounted on framework above the switch structure. The spacings of the wires are kept at 12 in. (30.4 cm.) or better for opposite polarities. Cambric-insulated flameproof wire is used throughout. Disconnecting switches are installed on both the high-tension and low-tension sides of the transformers, so that one transformer can be disconnected without interfering with the service. Where open wiring is used, it is always painted a standard color, such as red for 11,000 volts, drab for 2200 volts and white for 110 volts, and this arrangement of colors is adhered to throughout the system.

Diagram *B*, Fig. 15, shows the wiring of a layout of this type. Both incoming and outgoing lines feed through oil circuit

breakers to the high-tension bus. Disconnecting switches are always installed on each side of the oil breakers.

Fig. 9 shows, in section, the arrangement for a double-bus open wire construction. The double bus arrangement is necessary where different combinations of high-tension lines are desired. This installation is very compact, yet all wires have ample clearance for both safety and ease of construction and repairs.

The next step toward safety is the use of the cell structure.

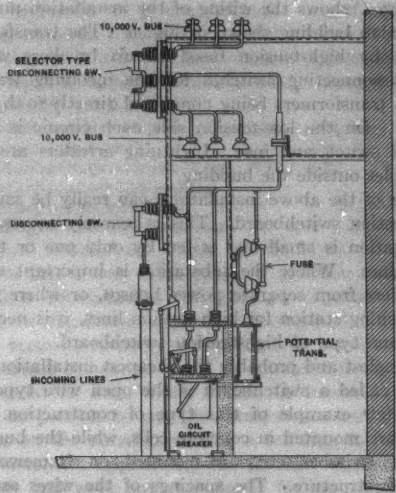

FIG. 9

In this arrangement all wires are separated by barriers of some description; soapstone, slate, concrete, ebony wood are some of the materials generally used. I will touch only on the use of concrete. This is probably the cheapest and gives a grounded surface for mounting the equipment, thus depending entirely upon the insulation of the apparatus.

When the cell structure is referred to, we usually think of something quite massive, but it is sometimes desirable to erect a cell structure and at the same time economize floor space.

Fig. 10 shows, in section, a double bus installation in which the busbars, series transformers, fuses and most of the disconnecting switches are mounted in compartments. The roof trusses are built through the cell structure, so that most of the available space is utilized. The lines enter through roof tubes between the vertical cell barriers. Connections to and from the oil switches are made with cambric-insulated wire

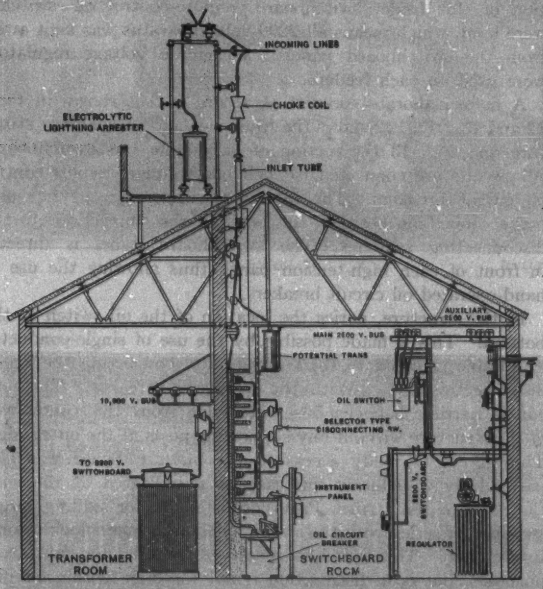

FIG. 10

in fiber conduit mounted in the concrete wall. To the right in the figure, the 2200-volt feeder switchboard, built in a double deck arrangement, is shown.

On the roof of the station are the outdoor electrolytic lightning arresters. A ladder is provided at the end of the building for use in getting to the roof to operate the arrester equipment.

Diagram *D*, Fig. 15, shows the wiring of this station. The

lines feed in through oil switches to selector type disconnecting switches, and thence to each of the buses. One bus is sectionalized so that some of the lines ordinarily feed through to other substations entirely independent of the load in this station.

Figure 11 shows the inside view of this station, with the high-tension concrete structure to the left and the 2200-volt incandescent feeder switchboard to the right. In the construction of this feeder switchboard, remote-control oil switches were used, which means all 2200-volt apparatus was kept away from the switchboard panels. Automatic voltage regulators were used on each feeder.

A more elaborate concrete structure is that shown in Figs. 12 and 13. Fig. 12 shows the front view of the concrete structure and Fig. 13 the section of a double bus switchboard. All circuits are connected to each bus through remote-control oil circuit breakers. The insulators supporting the bus also make connection between the bus and the connections to the disconnecting switches. The switchboard panel is directly in front of each high-tension panel, thus allowing the use of hand-operated oil circuit breakers.

In the structure, notice the location of the oil switch at the bottom. This is made possible by the use of single-conductor lead cable clamped to the concrete and connecting the upper disconnecting switch with the oil circuit breaker. The horizontal barriers between buses are hung from the center web of the structure without any supporting posts at the outer edge. This allows of ready access to the buses. Space was also particularly valuable in this case, as is indicated by the position of the roof truss. Provision is made for adding larger switches in series with the present ones on the main floor at some future time. This switchboard serves not only for substation purposes, but is a distribution board for high-tension circuits to other substations.

Diagram *E*, Fig. 15, shows the wiring of this switchboard. All circuits are double-throw on either bus. The buses are sectionalized by disconnecting switches to allow of greater flexibility in switching. The transmission lines can be operated in multiple or separately, each one feeding its own section of load. By operating separately, trouble on one section will not generally affect the other parts of the system.

FIG. 11 [FULLERTON]

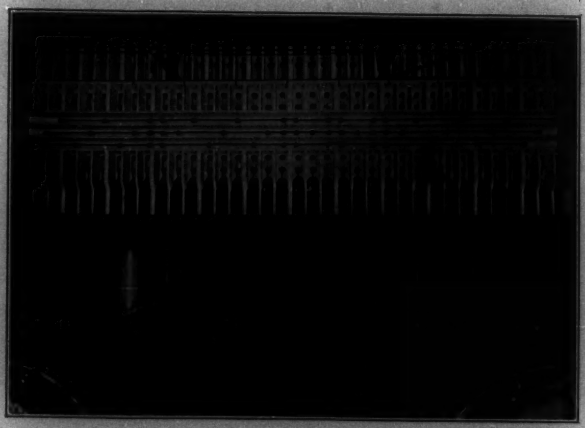

FIG. 12 [FULLERTON]

FIG. 14 [FULLERTON]

I cannot pass the subject of concrete cell structure without a few words regarding the method of construction. The usual method of building these cell structures is by erecting forms and pouring the concrete, using reinforcing rods where necessary. Owing to the difficulty of securing a uniform and smooth

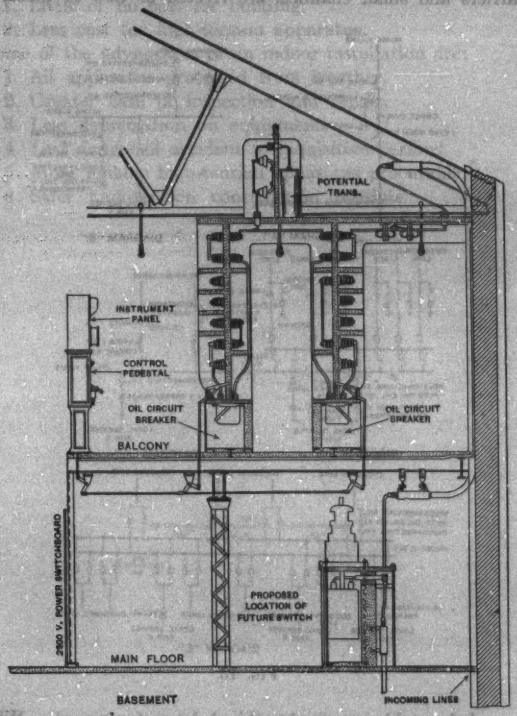

FIG. 13

job, we have digressed a little from the usual method and are building an expanded metal framework and plastering the concrete body onto it. The thickest portions plastered are three inches. The scratch coat contains a small quantity of hair, the remaining coats being pure cement and sand. The finishing

coat is of Keen cement, which gives a hard, white, smooth surface. In the finishing coat, a small quantity of lime is used to make the cement work more smooth.

Figure 14 gives an idea of the method of constructing the expanded metal framework. Angles are used in the heavy barriers and small channels are riveted or tied to these, the

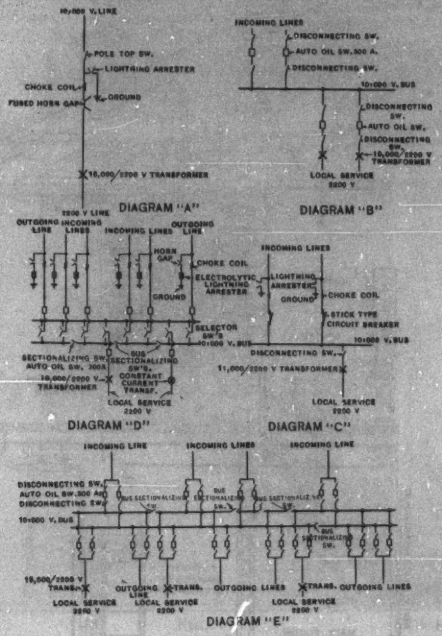

FIG. 15

expanded metal being wired to this skeleton framework. Where the structure is built as in Fig. 11, the reinforcing is keyed into the main wall.

COMPARISON OF OUTDOOR AND INDOOR INSTALLATIONS

In company substations, the field for the outdoor installation seems to be with the small towns which can be picked up

along the route of the transmission system without considerable line extension. Where larger municipalities are handled, it is usually desirable to install emergency service which requires more or less high-tension switching, and an indoor substation is usually desirable.

Some of the advantages of an outdoor installation are:

1. Little or no cost for building.
2. Less cost for high-tension apparatus.

Some of the advantages of an indoor installation are:

1. All apparatus protected from weather.
2. Greater ease of inspection and repair.
3. Less depreciation on equipment.
4. Less danger of accident to inquisitive persons.
5. More reliable high-tension apparatus procurable.
6. Safer high-tension construction possible.

Presented at the 2d Midwinter Convention of the American Institute of Electrical Engineers, New York, February 25, 1914, under the auspices of the Electric Power Committee.

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OUTDOOR SUBSTATIONS IN THE MIDDLE WEST

BY LESLIE L. PERRY

ABSTRACT OF PAPER

Conditions in the Middle West, particularly in the agricultural districts, have often been such as to necessitate the construction of small 33,000-volt outdoor substations in order to make the supply of current commercially practicable.

These stations have been constructed with very simple switching and protective equipment, and economy of design and protection to the main line have been the dominating feature of design.

Operation of such stations has been successful and they are of great benefit to the communities served.

Improvement in lighting and overload protection is looked for.

THE CONDITIONS in such states of the Middle West as Illinois, Indiana, and Kentucky, are very favorable to the use of small outdoor substations. Many of these have been built during the last year, and more undoubtedly will be built in the next few years. There is little very high-tension transmission within 300 miles (482.8 km.) of Chicago, but there is a large amount of 22,000-volt, 33,000-volt, and some 50,000-volt transmission. These lines for the most part serve districts that are not densely populated. In many sections, particularly in Illinois, the communities are almost purely agricultural, with only those small industries associated directly with agriculture.

In the manufacturing States, particularly in New England, oftentimes a factory or mill can readily supply electricity made either by water power or steam on a moderate investment cost and with a very low operating expense. But many of the richest agricultural districts of the Middle West are without small reliable water powers, and cheap, economical steam plants are impossible under the conditions.

Many towns of 2000 people have three-fourths of their people within a radius of a mile (1.6 km), and the entire electrical business of one of these towns may not warrant the expense of more than a single man devoting his entire attention to electric service. Where, as occasionally, local plants have

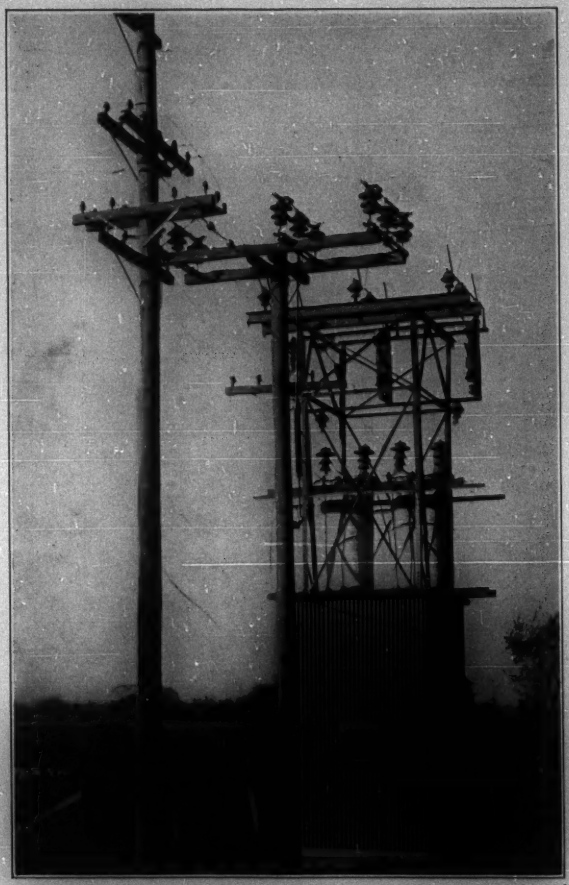
been built, they usually have rendered very indifferent service, and seldom operate throughout the 24 hours. With a distribution system of 33,000 volts nearby, of course continuous service can be readily given; but in order to make such service commercially possible, investment and operating costs must be kept within the lowest reasonable limits.

It frequently happens that such local plants as exist have not enough floor space or headroom to house 33,000-volt apparatus, and in other cases there are no suitable buildings, so that immediately there comes up the question of building investment.

In the climate of Chicago, it is the opinion of many engineers that somewhat more reliable operation will be had with indoor apparatus, and where housing has to be provided for considerable apparatus, such as street lighting equipment, feeder-regulators, and perhaps a motor-generator or a synchronous converter, the size of the load and the number of customers served warrants a new building. Of course, with voltages of 60,000 and above, the indoor station would not be possible where it can be used at 33,000. Where the load is below 300 kw. it is often considered that on voltages of 33,000 and above, the cost of any high-tension oil switch and aluminum cell arrester is not warranted, so that very simple outdoor high-tension switching and protective gear with the outdoor type transformers make a substation equipment well adapted to the requirements. Where no indoor space is available, just enough housing is provided to protect a low-tension oil switch, a watt-hour-meter, ammeter, and voltmeter, with space for a street lighting regulator if required.

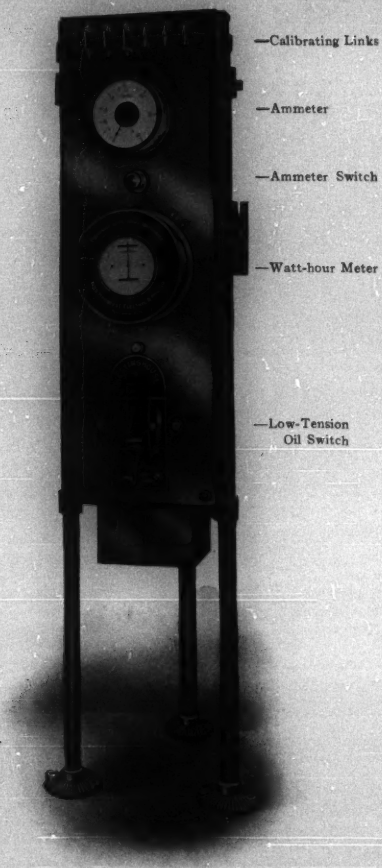
While many stations have supporting frames built of wood, undoubtedly more and more of them will be built of steel. At first thought one would consider the wood much cheaper; but taking into account that the steel structure can be built by efficient shop labor with minimum erecting costs, while the wood structure requires the less efficient field labor, and does not have the reliability, life, or freedom from fire risk that the steel does, it will be found the wood structure is not any cheaper.

A station to handle three 50-kw. transformers can be supported on a tower with a six-foot (1.8-m.) base as shown in Fig. 1. A six-foot square house of galvanized iron or heavy sheet steel is ample for most requirements and accommodates a 2300-volt low-tension panel as shown in Fig. 2, and incandescent outfit for street lighting.



[PERRY]

FIG. 1—33,000-VOLT OUTDOOR SUBSTATION EQUIPPED WITH TWO 50-KW. TRANSFORMERS AND SPACE FOR THIRD.



[PERRY]

FIG. 2—LOW-TENSION PANEL USED WITH OUTDOOR SUBSTATIONS.

These substations are connected to transmission lines supplying substations of larger size, say 600 kw. per station and above; provision should therefore be made to automatically cut free these outdoor substations from the transmission lines in case trouble develops in the small station. Hence, in the supply of power to the small rural station, the chief requisites to be met are: 1, economy of design, 2, protection to the main line, and 3, reliability of service in so far as the elements of the outdoor station itself are concerned.

Up to the present these stations have been very successful. The problems of overload and lightning protection have been solved with reasonable success, but unquestionably improvement can be made in these directions. In the absence of better devices of reasonable cost, either the plain wire fuses on horn gaps, or the liquid high-tension fuses with or without horn gaps, have been chiefly used for protecting the line, reliance being placed on the low-tension devices for overload on the substation itself.

For lightning protection a ground gap has been used, and the substation fuse is so mounted as to protect the line when the line current too freely follows the lightning. Choke coils are used in the transformer leads.

In designing such stations it should be remembered that they will often be in the hands of inexperienced operators, and hence every precaution should be taken to permit proper attention by ordinary emergency men; for this reason many stations have been built with disconnecting switches on a separate pole with lever gear such that the switch can be operated by any intelligent man. With this arrangement fuses can be replaced or defective transformers exchanged on a structure absolutely without any live wires connected to it.

In mounting the transformers well above ground, due regard has been paid to keeping the high-tension apparatus as free as possible from interference by careless or inquisitive boys, marauding animals, or the washerwoman's wind-blown laundry.

Sufficient success has been attained to demonstrate that by using these small outdoor stations good electric service can be supplied rural communities at attractive prices, and the central stations and the manufacturers are rendering true public service in reaching communities otherwise unable to benefit by central station service.

DISCUSSION ON "OUTDOOR VS. INDOOR SUBSTATIONS" (MACOMBER), "OUTDOOR SUBSTATIONS IN NEW ENGLAND" (HUNT), "INDOOR AND OUTDOOR SUBSTATIONS IN PENNSYLVANIA" (FULLERTON) AND "OUTDOOR SUBSTATIONS IN THE MIDDLE WEST" (PERRY). NEW YORK, FEBRUARY 25, 1914.

A. H. Kruesi: The time has passed for the discussion of the design of outdoor stations, and we must get down to the results of experience. The difference in cost generally between an indoor and an outdoor substation, taking buildings, equipment and steel structures, wiring, installation, etc., all into account, is generally not very large.

Mr. Hunt states that for the case he describes the difference is only about 11 per cent. That, I think, means that the outdoor substation should be restricted to comparatively small installations, like those, for example, which serve a single factory or industry. I think that for a substation which might cost anywhere from $20,000 to $50,000, a saving of $2000 to $5000 is altogether trifling, compared with the continuity of service which a city has the right to demand of a public service company, and that for such a small saving one would not be warranted in going to the outdoor construction if it can be shown that the risk of interruption due to the outdoor location of the apparatus is materially greater.

Two of these papers show photographs of outdoor stations for industrial plants using steel towers with the transformers placed on platforms on the towers. That makes the towers more expensive, due to the dead load, and the wind load, and I wonder if the transformers are put upon the platform as a matter of habit, because we have been hanging transformers on poles, or whether any real good is accomplished by having them up in the air. It costs more money, and in an emergency such as a burnout of a transformer it will require more time and money to take the defective transformer down and put a new one in its place.

A. R. Smith: The outdoor station is now some years old, and there are many of various capacities in existence, apparently giving satisfaction. The relative merits of the two types have frequently been discussed in a general way. What we want now are some records of actual operating troubles in different climates.

The reason for the existence of the outdoor station is economy, and there is no doubt that in many cases economy has resulted from the adoption of the outdoor station. There is, likewise, no doubt that many have been deceived in believing that they economized in resorting to the outdoor design.

The writer believes that there is a field for outdoor stations, and that the small transformer station of any potential without oil switches or attendants, and the large transformer or switching station of 60,000 volts and above, represent the two classes where economy in first cost can be shown. However, the saving in the

latter is largely a matter of the system of connections adopted.

There are many considerations as regards the choice between the indoor and outdoor station which have not been generally discussed and which the writer would like to suggest, with the hope that further data will be forthcoming. In fact, engineers in general are uncertain as to which policy should be pursued, and more enlightenment on the subject will enable us to proceed along definite lines with much greater assurance.

Oil-cooled transformers. The capacity of an oil-cooled transformer is wholly dependent on the area of radiating surface and the rate of heat transmission per unit of surface. The temperature of the transformer case when exposed to the sun may be from 15 to 20 deg. fahr. hotter than if protected from the sun's rays. If the temperature of the oil is 135 deg. fahr. and that of the case is 115 deg. fahr., the difference of 20 deg. gives the factor of heat transmission. Now, if the case were shaded, the difference would be from 35 to 40 deg., which means that the outdoor transformer has to be much larger.

It has been suggested that the transformer tanks be painted a light color to retard the heat absorption, and this should be effective; but the radiation of heat from the tank to the air is something like a ratio of 14 to 19 for light and dark colored surfaces, so that the net gain is a question.

The radiation is also directly affected by the velocity of air due to the convection currents caused by the heat emitted from the transformer. In the case of an outdoor transformer the height of the chimney effect is approximately the height of the transformer, as the heated air is immediately diffused after leaving the top of the transformer. On the other hand, the ventilation of an indoor transformer can be directed and controlled so that a uniform circulation on all sides is maintained and a chimney effect of two or three times the height of the transformer obtained. It may be argued that the relative costs of the two types of stations have been based on the manufacturer's costs of the two types of transformers; but the manufacturer has been obliged to use a factor of safety on indoor transformers much too high because so many transformers have been placed in buildings without any consideration for ventilation. Now, give the manufacturer a drawing showing a perfectly ventilated building for the transformer and then compare the costs of the indoor transformer with the outdoor transformer having more radiating surface or smaller copper and core losses; outdoor bushings; water-tight covers; non-freezing oil, or the capitalization of the losses due to exciting idle transformers; heating coils, and the capitalization of losses in the same, and we will find a greater difference than anticipated.

Water-cooled transformers. Water-cooled transformers are better suited for outdoor service, but these too have objectionable features. First, the water has to be kept in circulation in all idle transformers every day that the temperature is below 32 deg. fahr., which entails a pumping expense, and extra valves and

drains are necessary so that no water is left standing in dead-end pipes when a transformer is removed in cold weather. Second, oil-drain piping has to be designed without pockets which might become filled with moisture of condensation and freeze, and all valves have to be kept in working order. Third, the circulation of water in an idle transformer has a tendency to keep the oil from freezing, but it might be necessary to arrange to use the warm water obtained from the transformers in operation and then, at the best, this is very ineffective as the water coils are at the top of the transformer and all heat transmitted to the oil at the bottom is by conduction and not by convection.

In general, the heat produced by the transformers is wasted in winter when it is most needed, and in summer, when it is difficult to dispose of the heat, the transformers are located in the warmest place—in the sun.

Lightning arresters. With an efficient electrolyte the film dissolution on the cones is very rapid when the temperature exceeds 100 deg. fahr. To insulate the arrester tanks from the sun's rays is objectionable because it confines the heat if the arrester is discharging frequently. It has therefore occasionally been necessary to protect the arrester by means of a sunshade.

Oil switches. During rainy weather short-circuits are most prevalent, and it is often advisable to inspect the oil switch contacts after rupturing a severe short-circuit. In the case of the outdoor oil switch, this can only be done in wet weather by removing the switch to the repair shed, because of the possibility of permitting moisture to enter the tanks.

It has long been acknowledged in the design of steam plants that apparatus located in hot, wet or inaccessible places does not get the attention from the operator that it should. Now, how much attention is going to be given to the oil switch operating mechanism during stormy weather? Will not repairs and inspection be postponed for more favorable weather? What is the possibility of the switch failing to open due to this lack of attention and postponement of repairs? What is the life of a switch and consequent depreciation of an outdoor switch as compared with an indoor switch, and what does it cost to provide facilities for transporting the oil switch to the repair shop upon the least provocation?

In some outdoor installations it has been necessary to provide by-pass disconnecting switches so that the switch could be left in disuse until a favorable opportunity presented itself for repairs.

High-tension wiring. Buses and disconnecting switches are the safest to locate out of doors, and they really require the most building space. A semi-outdoor station is possible and economical with certain wiring connections, where the apparatus is protected by a moderate size building, and all of the wiring located out of doors.

Fire risk. It is frequently claimed that the outdoor station is a better fire risk than the indoor station; but this may or may

not be true. The spacing between conductors out of doors may be considerably greater, but at least 50 per cent greater spacing is necessary to obtain the same factor of safety, because of the rain and the wind which will start an arc sooner and carry it farther. Then there is the transformer fire risk. We can readily imagine the resulting damage if a transformer should get on fire adjacent to a steel tower, the failure of which might result in the collapse of the entire steel structure of bridges so often employed.

Facility of making additions. The outdoor station can readily be added to or changed; but it cannot be readily housed in if the outdoor scheme is found unsuited for the climatic conditions. Furthermore, if all of the money is invested in the apparatus, the cost of replacing it due to obsolescence, inadequacy or depreciation is proportionally increased. The life of a building is usually considered to be at least twice that of the apparatus.

General considerations. The maintenance of the outdoor station structures should not be materially different from the building structure, as the steel towers should be painted, provided the wiring is arranged to make painting possible, and the walks, foundations, fences, repair shop, and operating house kept in repair. The cost of maintenance of the outside apparatus will probably be more than the inside apparatus.

In cold climates there are the snowfalls and drifts to contend with, which means extensive shoveling of paths, and the clearing of the tracks and turn-tables of ice. And during electrical storms, all of the apparatus is exposed to a direct stroke of lightning, as choke coils cannot conveniently be arranged always to direct the lightning to the arresters.

These objections are set forth, not with a view to discourage the use of outdoor stations, but to show that the saving of a $25,000 or $50,000 building does not necessarily represent the net saving, and that the resulting saving is not always sufficient to warrant the adoption of the outdoor station, if reliability is to be sacrificed or maintenance increased.

Roy E. Argersinger: We must see a very large saving in order to make the outdoor substation worth while, as I believe the danger we run into ought to be very seriously considered. For instance, if we get a bad storm, we are more likely to get trouble at that time than when the sun is shining, and we do not want to go out and pull the transformer apart when a heavy storm is raging. It is hard to get any one to work on the outdoor substations during such conditions. During the last week in our country we have had the thermometer down to 15 and 18 deg. below zero, and it is hard to get linemen to look at the line, to say nothing of the station, under such conditions.

H. B. Gear: It seems to me that the economic question whether or not the outdoor substation pays is very largely a question of determining the balance between the cost of the building and the cost of the rest of the equipment. In industrial substations running from 150 kw. to 1000 kw., the possibility of an outside

substation is just as likely to be fixed by local conditions as by the desirability of saving the cost of a building. In some manufacturing plants there is no available space for the placing of a substation. The equipment must be placed on poles in the public thoroughfare or installed in a vault, if the line is underground.

For the smaller substations it is not entirely an economic question. The cost of the building, if a separate building is erected for the purpose, is apt to be as much or more than the cost of the equipment itself in the smaller sizes, and therefore anything in the way of an enclosing building becomes a considerable addition to the total investment.

As we pass up to the higher capacities, and where the outdoor installation becomes desirable, because of the fact that the service is supplied by very high voltages, the problem becomes a little different. The tremendous separation required for 66,000 volts, naturally suggests putting the apparatus outdoors rather than building a structure big enough to provide necessary clearances. In the case shown in one of the papers, the saving figured out is about 11 per cent. At lower voltages, and with large substations such as are found in metropolitan work, with several thousand kilowatts involved, the amount which may be saved is a much smaller percentage, since the potential regulators, the switchboard equipment and all the accessories required in distributing from a substation, as a matter of giving good service, must be placed indoors, and only the transformers and the switching equipment could go outdoors. In this class of installation, it will not often be found that a great deal can be saved by building an outdoor substation for the transformer equipment.

The point which is touched on in Mr. Perry's paper with regard to the use of outdoor substations in high-tension distribution is an important one. The ability to serve large areas by means of 33,000 volts, as is being done in Northern Illinois, is dependent largely upon the possibility of locating comparatively small substation equipment out of doors. There are numerous cases where transformers as small as 50 kw. are supplying towns along the route of the line in which it is possible to give fairly good service without anything but a platform and a little local construction. This would not be possible from an economic point of view, if it was necessary to construct a building and use the type of equipment which was considered necessary for a substation a decade ago. Outdoor construction may be applied in a variety of ways and has a very definite place in electric distribution.

W. S. Moody: The four papers that have been presented on outdoor transformer stations give a very good general review of a recent development in our art. It is not a radical improvement in the sense that it requires any great change in previous methods of designing apparatus, or any inventive ability on the part of the manufacturer, and yet, it does mark an important epoch

in electrical developments, which, I believe, will be more fully appreciated as the practise becomes more general.

As has been pointed out, the innovation in practise started purely on its economic showing. Both the manufacturer and the operator shrank a little from the idea at first, because it clearly increased the risk for both, but none of the various possible sources of trouble are really inherent and it only needed, therefore, some experience and a close and intelligent study of details to avoid them.

If I may be allowed, I will point out two respects in which the papers do not give an entirely correct idea as to how far this practise has progressed. It is stated that there is something like 300,000 kv-a. in outdoor transformers installed or contracted for. Those for whose design I am responsible alone amount to 25 per cent more than this figure, so it is fair to assume that the actual capacity of such transformers so far produced may be nearer 600,000 than 300,000.

The other incomplete impression given is as to the maximum size of units and installations. Units have already been built up to at least 7500 kv-a., and installations up to 50,000 kv-a.

The most important features to be cared for in an outdoor design (as far as our experience yet goes) are:

(a) Covers, joints around leads, man-holes, etc., must be thoroughly weather-proof. This not only means that they be rain-proof, but so completely sealed as to be water-tight when ice and snow build up and hold water over the joints.

(b) That the leads be made of such material and in such a manner as to be entirely unaffected by the weather.

(c) That the tanks be so ventilated that they will not take in rain or snow and yet may relieve themselves from moisture and gases.

(d) That idle units be heated sufficiently to avoid their being at a temperature lower than the atmosphere.

I want, in closing, to say a word of caution with reference to the needless use of outdoor installations. Some people are anxious to use the latest thing, whether it is best for their conditions or not. It should be borne in mind that however well the apparatus may be designed for outdoor service, it cannot be quite so safe or convenient when so installed as if it were protected from the weather, consequently the lower cost of installation and possibly a little less fire risk are the sole reasons for outdoor installation, yet I have seen such installations right beside large stations that had and probably always will have more than ample space for the transformers inside. In such cases considerable extra expense had to be incurred in carrying both high- and low-tension wiring, already inside of the building, out to the transformers and back. Such an installation made simply to be in style is certainly not good engineering.

Allen M. Rossman: Mr. Kruesi asked the reason for putting the transformers in various substations above the ground. With

reference to the substation shown in Mr. Perry's paper, there were two considerations which led to this design;—one was to keep the 33,000-volt wiring up out of the way; the other was to provide, within the structure, a housing for the low-tension (2300-volt) meters and switches and for an arc lighting transformer, if needed. Consequently, the whole substation is self-contained.

I might say, regarding the cost of this particular substation, that the structural steel as shown, together with the fuses, horn gaps, choke coils and disconnecting switches complete—the structural steel being galvanized—cost very little more than would a first-class 33,000-volt oil switch, and it is only by reason of this low first cost of substation that an extensive 33,000-volt distribution system supplying a large number of small scattered customers is possible.

J. C. Smith: We have had very little experience with the large outdoor type of substation around Montreal, and in other sections of Canada, probably because the use of an outdoor substation would involve the use of naturally cooled transformers. We could not use water-cooled transformers on account of the temperature conditions. For example, at our power plant, for the last four weeks the temperature has not risen above zero, so that you can imagine to take care of water-cooled transformers would be quite a difficult task. So that while we have done considerable calculating on the subject, the matter always resolves itself into the fact that it would be necessary to put in, at very considerable extra expense, means for protecting the apparatus from the cold, and we have not yet had enough confidence in the oil switches to feel that we could operate them successfully under these very severe climatic conditions.

P. W. Sothman: I think I will have to agree with Mr. Smith in his remarks on this matter, as to the reason why it was decided that Ontario was not the place for the outdoor substation. I believe we would have had to spend more money for heating up the system, than for keeping it cool. In a general way I think the matter of outdoor substations should be dealt with on its merits. I think, without any question, there is a big field for the outdoor substation. On the other hand, I think there are many places where the outdoor substation is not the one which is needed. The comparison of cost, between the outdoor and indoor substation, may play, to a certain extent, some part in the matter, but I think, from the operating standpoint, we should be very careful to draw the line between saving a few per cent and then running a risk of destroying the necessary continuity of the service which is essential above all things.

When we look over the liabilities which a public service corporation assumes, when we look at the mistakes which have been made in certain sections of the country by the saving of a few cents, and thus weakening the guarantee of a fairly good service, due to not properly protecting the system, or some part of the

system, we soon come to the conclusion that such a policy is very bad engineering. I think the motto should be, first of all, continuous service, if possible, within commercial reason. If we are guided by this consideration, and in addition give proper attention to the climatic conditions, I think that will tell us where an outdoor substation should be built and where an indoor substation should be built. I think also we will see, to a certain extent, the combination some day of the indoor-outdoor substation even in big cities.

J. Edward Kearns: A careful analysis of this subject will resolve itself into two factors: first, that representing continuity of service, and second, the question of cost, including not only first cost but maintenance and depreciation.

With respect to continuity of service, the principal point, of course, is to be careful to select apparatus best suited for local conditions and that which will eliminate, as far as may be, all possibilities of shut-down. When we come to the question of first cost, a careful comparison has been made of several outdoor substations and indoor substations, which shows that the outdoor type is about 10 per cent to 15 per cent cheaper, in sizes of 2000 to 5000 kv-a. Now, perhaps, the main reason why the cost of the indoor substation exceeded that of the outdoor substation, has been due to the type of building and other architectural features brought into the construction of the building. I personally feel quite positive that if more of our smaller indoor substations were built with a very cheap sheet metal building, we would find that the general comparison would be about equal, particularly if we keep in mind the fact that it is always desirable to have an attendant when large outdoor substations of 10,000 to 20,000 kw. are installed, and, under these latter conditions, I believe it will be found that the general result will be very much in favor of the indoor type of substation.

Another important subject that has been brought out in the discussion, in addition to these two, is the question of climatic conditions, and large installations to date indicate that less trouble may be experienced with outdoor substations in southern climates than those in the northern or cooler climates, with the result that many operating companies in the North are not installing outdoor type substations, but are considering instead a very cheaply housed substation.

K. C. Randall: The very pronounced increase in the reliability of apparatus in general, especially that which is involved in outdoor installations, has contributed immensely to the practicability of the outdoor station. Transformers and breakers have been simplified, strengthened and made more substantial and reliable, with more permanent factors of safety, so that now under nearly all conditions they can be looked upon as largely free from the need of attention.

As an economic problem, there is no doubt that good consideration is required to determine definitely the justification

of the outdoor station, or, so far as that is concerned, of the indoor station. It is also possible that fashion may have brought outdoor stations into being when the indoor station might have been better, but the same can be said of the indoor station. Probably there are few men with experience who can not recall instances where the outdoor station would have been a better proposition than the indoor station which was built.

Terminals for apparatus and station outlets are so thoroughly developed, that very little or no trouble is encountered from those of best design. These were the original stumbling blocks when the outdoor apparatus for heavy potentials was first undertaken. Terminals that will stand 300,000 volts in a 45 deg. precipitation of ½ in. per minute are in use and are entirely practicable. Terminals for all lower voltages and current ratings have been developed with equal success.

The first 100,000-volt transmission in this country, whose transformers were built under my direction, operated without lightning arresters entirely successfully with a grounded overhead line wire extending but a few miles from the stations where the transformers were installed. This was some years ago. There is no doubt that transformers of today are equally reliable, which means that the necessity for repair is remote. The same applies to switching apparatus and therefore, in general, the outdoor equipment is not likely to demand much attention.

Five years ago this subject was presented before the Institute, and it was then suggested that the outdoor station would have a place under some conditions but that no general rule could be stated for determining when the outdoor station would be justified. The four papers presented today have shown that there have been applications for an outdoor station which have been justified, for it is not reasonable to assume that all, or even many, having made these installations have been wrong in their judgment.

It is, therefore, gratifying to me to have this confirmation of the opinion then expressed. At that time many doubted, according to their discussion, and even today the same attitude would seem to prevail in some places, although the practicability and desirability of the outdoor station have been thoroughly confirmed.

Henson E. Bussey: We have quite a large number of outdoor substations. The capacities of these outdoor substations run from 20,000 to 30,000 kw., but it has always been an open question with me as to whether or not there was not a little bit of stampeding in building outdoor substations in our climate. A great many people seem to think that the South is a particularly good climate for outdoor substations. I do not think so, for the reason that very frequently we have rainfall at the rate of as much as three to four inches an hour, and at the same time extremely high winds, and if transformer tanks and switch tanks are not absolutely tight, then undoubtedly trouble

is going to develop. As to whether or not that trouble will develop, it is a question of simply waiting to see. It has not developed so far.

It seems to me that the relative advantage of outdoor versus indoor substations for any climate lies in the question of the first cost, as has been brought out, and in the reliability of operation. The question of the first cost is something which the companies which have been building these substations can very materially assist in settling. I would like to know whether or not the outdoor substations are really cheaper, considering the same class of installation, than the indoor. I very seriously doubt it. I know of one case of a 20,000-kw. outdoor substation—five of them, in fact, which were built on the same system, where the people who had charge of the building stated that it worked out in advance very much cheaper than would have been the case had they used indoor substations. After they had been built, I found that they worked out nearly fifty per cent in excess of the estimates, and now it is a question whether or not they are cheaper. It is safe to say that they could have built the indoor substation as cheap, if not cheaper.

The character of the building is an important factor, but I am firmly convinced if we could get some data from the operating companies and the people who are constructing the buildings and substations, the point will be settled once for all.

E. A. Lof: One point that must be given considerable attention in connection with outdoor substations is the protection of the transformers, both from the extreme heat in summer and from the cold in winter. While the former can be readily obtained by providing sunshades, in certain instances very good results are obtained, as stated by one of the authors, by simply painting the tanks white.

It is, however, more difficult to provide for the cold winter temperatures, especially with water-cooled transformers. With the transformers in service there seems to be no danger of freezing, and for this reason the transformers should be connected to the circuit and thus energized even if they do not carry any load. Some sort of heating grids can also be readily provided in the bottom of the tanks. The main difficulty lies in the formation of moisture which takes place when the temperature of the transformer is allowed to fall below that of the surrounding air. This applies equally well to indoor transformers, and precautions must therefore always be taken to prevent this. Much may be accomplished either by reducing the water rate at times of cold weather, or by using the cooling water over and over again.

There are a number of other points which should be given consideration in the construction of the outdoor substation. The line wires should be securely anchored before entering the station structure, and no unnecessary strains should be permitted in the wires inside the structure. Consideration should

be given to deflections resulting from different pulls on the connections, and also to unequal settlement of supporting towers which may readily cause excessive stresses and insulator breakages, resulting in service interruptions. The spacing of all the conductors, as well as that of apparatus, should be liberal, but not excessive.

The transformers and switches should be placed on concrete foundations of a sufficient height to be clear of water, and the station should furthermore be well paved and drained around the apparatus. Transfer tracks with a truck will also be found very convenient when moving the apparatus. Cement walks should be laid on that portion of the ground where the operator is most apt to pass in his inspection trips and work about the place. The oil piping to the transformers and switches, and the water piping, if water-cooled transformers are provided, should be so arranged that connection can be made or broken for any unit without disturbing the operation of the other.

Farley Osgood: In New Jersey we have no outdoor type of substation as described in these papers. We do not get the isolated conditions in our territory, which warrant such an installation, and the service is so congested, and in New Jersey is coupled together with railway service, demanding so much continuous switching, that it is questionable if the outdoor type of substation left a good deal by itself would work with us. The New Jersey territory, generally speaking, is a well solidified field of operation, with a good many substations, not very far apart, and the demands of combined service require so much personal attendance, that it is very doubtful, except in developing the outskirts of the territory, if anything but the indoor type of station would be installed. Our problems are simple, because our voltage is 13,000.

Dugald C. Jackson: I want to express this proposition as one that runs through my mind—and I think it is pretty definitely fixed there—that in the case of large substations on which a great deal depends, reliability becomes a matter of the very greatest importance, and under these circumstances the cost of the building is so small a factor of the total investment cost for the distribution system, and converting apparatus and real estate, that the saving of 20 per cent, or even 50 per cent, of the cost of the building alone may not be a factor to be considered, and consequently large substations, especially those serving cities, should ordinarily be housed under the very best conditions of fire-proof construction.

But there is a different condition to be considered, and that condition is well illustrated in Mr. Perry's paper, also in Mr. Fullerton's paper, and to some degree in Mr. Hunt's paper. It would be again illustrated if we had a paper from the Rocky Mountain region. There one has vast areas—the Rocky Mountain region is sparsely populated, the same is true of parts of the prairies of the Central West; and it is even true, in part, of

the state of Massachusetts, which, next to Rhode Island, is on the average the most populous state in the Union per square mile, yet there is a good part of Massachusetts in which the population is very sparse—this is also true of the states of New Hampshire, Vermont and Maine. In such sparsely populated territory, there is here and there a customer who should be provided with power, or a small village which should be provided with power, where, perhaps, in the past they had a small electric lighting plant of their own, but have been seeking better service afforded on a more favorable basis.

These needs of isolated individual customers and small villages of the Far West, of the Central Western prairies, probably the South, and of New England, can be served by outdoor substations, or, perhaps, by what have been called outdoor-indoor substations. Mr. Fullerton describes the latter fully and admirably. The latter development is one which seems to me to possess great economic possibilities for electrical engineering, because it may aid in the making of another step toward putting power transmission into the same category of comprehensive usefulness and importance as transportation and the transmission of intelligence.

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PROBLEMS OF HIGH-TENSION TRANSMISSION LINES

REPORT OF SUB-COMMITTEE ON TRANSMISSION

P. W. SOTHMAN, CHAIRMAN

Introductory

IT IS not intended that the following article shall completely cover the very broad subject of transmission of electrical energy, but only outline some of the more important problems which have to be considered when building and operating high-voltage lines. Such data as are contained herein have been supplied by the members of the sub-committee with the idea of furnishing a basis for discussion, for it is recognized that the principal value of a paper of this kind lies in the discussion which it may elicit.

Some of the topics of particular interest at this time have been treated in short special articles which are published as appendices to this report and which appear under the names of their respective writers.

Right-of-Way

In sparsely settled countries there is generally no trouble in securing as much land as may be needed for the erection of the transmission and telephone lines, and the only point to bear in mind is the choice of route involving the least constructional difficulties, such as the crossing of mountain ranges and streams or the avoiding of locations which make patrolling and maintenance unduly expensive. If a restricted locality were known to be particularly subject to lightning storms, this would naturally be avoided, if possible.

On the other hand, in districts like the East where the land is already fully occupied and sometimes quite valuable, the right-of-way problem is often not an easy one, and the question arises as to whether it may not be advisable to obtain easements, giving the company the right to erect and maintain its lines across the lands of the owners. Tower lines may even cross fields under cultivation, causing practically no inconvenience to the farmers, who have been known in many cases even to plow and grow grain between the legs of the towers themselves. For

convenience in patrolling and the making of repairs, the route should, as far as possible, be chosen alongside of highways, regardless of whether the right-of-way is purchased outright or not. The width of right-of-way is an important consideration, as well as the minimum clearances which should be allowed above ground.

There are cases in which it may sometimes be advisable to utilize the right-of-way of an existing steam or electric railway, provided a suitable agreement can be reached between the respective parties. This arrangement has been objected to at different times by laymen because of the alleged danger to the traveling public. That this objection is groundless, we all know, and decisions have been rendered by at least one State Public Service Commission to this effect. Objection to this practise has also been made by the telegraph companies occupying the same rights-of-way, on account of the interference which may be set up in such circuits because of the proximity of the power lines. By the use of proper care these troubles may be reduced so as to become unimportant, so that this objection also is overcome.

Under this heading may also be included the constructions necessary for the crossings of railways and other circuits. There is at present no generally recognized type of crossing protection, and whatever kinds are used are usually subjects for agreement between the parties concerned. Certain protection from falling wires or cables is desirable, but we feel that the matter has been carried to extremes in many instances. If two power companies adopt elaborate and expensive means for protecting their respective circuits where crossing one another, when an ordinarily substantial construction of the lines themselves would suffice, how can they object if the telephone and telegraph companies, whose lines they have to cross, insist that an equally elaborate protection be installed for their crossings also? This shows the need for an intelligent agreement upon the subject and for a code of rules or specifications, preferably bearing the sanction of the Institute, which will be accepted by all parties. Such specifications should allow a certain latitude in the construction so as not to inflict unnecessary hardships upon small power companies operating at comparatively low voltages, or those located in unsettled districts.

Towers

The selection of the type of tower depends upon the number of circuits to be carried, line voltage, whether suspension or

pin type insulators will be used, the physical characteristics of the country through which the line will pass, and also upon the climate. It is generally agreed that the square or four-legged tower is more efficient in the use of material than the three-legged tower and the latter is seldom seen nowadays in new work. The flexible type of tower has also been used to some extent with good results, but it is necessary to place rigid towers at frequent intervals along the line to act as stays, from which the flexible towers are more or less supported by the overhead ground wires and also by the power cables when pin insulators are employed. It is too early to say what success will attend the flexible tower when used in connection with long suspension insulator strings, and until more data are available upon the subject it is advisable to proceed with caution when considering the adoption of this construction.

Where suspension insulators are employed, it has been found that it is not good practise to place two or more conductors in a vertical plane, especially where snow and ice are liable to collect upon the cables. When this load breaks away it very seldom does so uniformly and the cables are in great danger of coming into contact. This phenomenon has been quite fully treated in a recent paper. It might be added that it has been observed in the East that ice seems to collect to a greater extent at the centres of the spans than near the towers, which should be taken into consideration.

The method of calculation of tower designs should be standardized, and the constants for such materials as copper, aluminum and steel used for conductors should be taken at some acceptable figure such as 30,000 lb. for copper, and 14,000 lb. for aluminum, as representing the elastic limit of the material. The design should be calculated so that when the loads estimated are all on, the structure will be stressed to the elastic limit. The factor of safety is therefore in assuming excess loads over those which are known to be liable to happen.

Ordinarily towers should not be calculated, but they should be specified to stand certain loadings, and should be tested for these figures.

Foundations. It is very important in the use of rigid towers to see that the foundations on which the tower stands are all at the same height, and therefore, it should be specified that the foundations of the tower should have their tops within 1/10 of an inch of the same height.

Minimum Thickness of Material. In the construction of towers no material should be used less than 3/16 in. (4.7 mm.) in thickness.

Bolted Connections. It is recommended that the minimum number of bolts in any connection be not less than two.

Strength of Members. It should be kept in mind in the design of the towers that men are likely to climb up and down the towers on the angles, and therefore, one of the limiting conditions is to see that no members are used which would be bent by the weight of a man in so climbing a tower.

Movement of Wires. It would seem advisable to increase the customary figure of 45 deg. used for angle of deflection of the insulators to 55 deg. or 60 deg. from vertical, under the worst wind conditions.

The effect of ice and sleet should be considered, and this from the point of view of non-uniform loading. The structure should be so designed as to permit the loading of one span with the two adjacent spans not loaded, and still have sufficient clearance between all the wires so that under these conditions there would not be probable contact due to wind conditions.

Amount of Sleet. Not less than ¾ in. (19 mm.) of sleet or ice for the northeastern part of the United States and the eastern part of Canada should be allowed for.

Wind Load. The wind load is heaviest at times of sleet, and it should be recognized that the sleet does not form uniformly around the wires, but that the section of the ice is more or less elliptical.

Wind Pressure. It would seem advisable to increase the amount of wind pressure for the eastern part of Canada and the United States to about 15 lb. (6.8 kg.) pressure per sq. ft. (0.09 sq. m.) on the round surface.

The usual method of erecting towers is to assemble them lying on the ground and then tilt them into place, which is apt to induce faults in them, hence it is very necessary that a careful inspection be made of them after erection, with a view to tightening up the bolts and examining the various members to see whether they are distorted.

In many cases towers have been provided with insufficient means for supporting and firmly holding the ground cables. The ground cable clamps should be quite long and have not less than four bolts so that the cables cannot possibly slip, allowing them to sag down in contact with the power conductors.

Galvanizing and Painting. From reports received from various quarters it appears that the galvanizing of steel towers is generally preferred to painting. Probably the manufacturers themselves differ more on this point than the users of towers. One manufacturer advocates painting because of the simplicity obtained in erection by having the sides of the towers assembled complete and riveted in the shops, only the cross members requiring to be bolted together in the field. Large pieces assembled in this manner cannot well be galvanized and painting must be resorted to.

Paint affords a good protection if the structures are periodically gone over and carefully scraped and cleaned before the paint is applied. It is very difficult, however, to reach all small interstices and pockets and these are the places where rust is most apt to occur. Superficial inspection frequently will not disclose rusting which may be occurring beneath the paint coating. There is no doubt that periodical repainting is more neglected than otherwise.

Galvanizing, on the other hand, practically eliminates worry and expense for maintenance, as it is electro-positive to iron. The galvanized coating has two functions to perform. In the first place, it is designed to keep the surface of the steel from coming into contact with water and the atmosphere, and secondly, it protects the iron whenever water and oxygen finally succeed in breaking through.

If the galvanizing is properly done, it may be relied upon to be in good condition at the expiration of 12 or 15 years, whereas painting cannot be depended upon much longer than two or three years, especially where the atmosphere contains sulphur or other fumes.

Footings extending into the earth may be galvanized with good success in most soils, although there are earths where asphaltum paint coating is more durable. In cases where extreme acidity or electrolytic action is expected in the soil, it is more economical in the long run to provide a concrete footing thoroughly encasing the steel.

Conductors

The relative merits of copper and aluminum conductors have been discussed quite often and it is not our intention to open the subject again at this time. A thorough understanding of the different qualities of the two metals should be had by engineers designing transmission lines, especially where suspension

type insulators are considered, in order that advantage can be taken of these qualities. There are certainly places where aluminum should not be used for power conductors, but on the other hand, there are quite often cases where it might be used to better advantage than copper.

Experience has shown that hard-drawn copper cables should not have hemp centers, for an action partly chemical and partly mechanical is set up which sooner or later weakens the strands and causes the cable to part.

In order to secure a greater strength and also partly to add weight to the cable a steel core has been inserted in some of the aluminum cables recently manufactured. While it is claimed by the makers that such cables are as durable as the ordinary aluminum cables and free from electrolytic corrosion, conclusive proof upon this is still lacking. It is understood that steel cores in aluminum cables are not considered satisfactory by English cable manufacturers.

For long spans where great strength is required, wires and cables made of steel having a coating of copper (copper-clad steel) are available, which give very good results. These wires are still too high in cost to be used generally for power conductors. They are coming into use to a certain extent, however, for telephone and telegraph lines.

In passing, it may not be out of the way to remark that there are several formulas in existence, all more or less tedious in their application, for the calculation of cable sags, taking into account temperature changes as well as spans and tensions. The majority of these are adaptations of the parabola formula and will give sufficiently accurate results so long as the spans and sags are moderate. We would suggest that some simple method, such as a set of curves, be evolved, based preferably on the catenary, from which the sags may be quickly and accurately determined for all possible conditions.

Ground Wires. It is generally agreed that overhead ground wires are beneficial as a protection against lightning. Just how much protection is actually afforded, however, is still a mooted point. A report given below, on this subject, from one of the large companies in the West, well illustrates the feelings of a majority of operating engineers.

This company has about 450 miles (724 km.) of 60,000-volt pole line without overhead ground wires, and about 100 miles (160 km.) with the overhead ground wire.

In the case of one particular branch about 42 miles (67.5 km.) long, running northerly, we feel that we have had reliable and conclusive evidence that the overhead ground wire does protect. We have had a number of thunder storms cross this line at right angles, and while lightning would sometimes cause the automatic oil switches to open at the power station, yet no real damage occurred to either the line conductor or insulators, neither were the poles split by the lightning discharges. In other words, service could be re-established at once. On the other hand, these same storms would sometimes destroy pin type insulators and pole tops, on lines not protected with the overhead ground wire, and the general opinion has therefore been formed that the overhead ground wire does protect against material of the line being destroyed. However, we do not have either the number or severity of lightning storms that a large portion of the states do. We have, on all new work permitting the expense, equipped our lines with the overhead ground wires.

We might add, however, that the testimony is not altogether in one direction. While we have had very good direct evidence of the usefulness of the ground wire in one line, on another line we have had several insulators shattered, notwithstanding two ground wires on the top of a steel tower transmission line. These troubles, however, have been due to what we are quite sure have been direct strokes of lightning.

Insulators

Reports received from various parts of the country indicate that the suspension insulator as usually manufactured, in the disk type with metal caps and pin, is quite satisfactory when new, accomplishing the purpose for which it is intended, up to voltages of at least 150,000. The fly in the ointment, however, is that after they have been a year or two in service, failures begin to occur, and as time goes on a large number of the sections have to be replaced. To insure steady service on the lines the insulators have to be inspected at frequent intervals to weed out any that have become faulty. This trouble is not confined to any make of insulator nor to any section of the country. Extracts from reports from several companies are given herewith which will serve to show how prevalent the difficulty is and the means employed for inspection. The first report deals with conditions encountered on the lines of two or three companies in the South.

The Carolinas experienced very severe lightning during the past summer. Following repeated failures of insulators in a limited portion of a certain line, under the writer's observation, it was believed that there might exist insulators which were punctured, but of which no external signs were visible.

The line in question consisted of a single and double circuit steel tower line, equipped with suspension insulators and one ground wire.

It was accordingly determined to see if it was possible to locate any such punctured insulators by means of a megger.

A megger was secured, giving 500 volts, and reading 1000 megohms, The method of procedure was as follows:

On a single-circuit tower line a party was organized consisting of engineer in charge of megger, and six linemen, working in pairs. One pair would proceed to ground the line on a certain tower and hold the leads of the megger, which consist of about 100 ft. (30.4 m.) of standard lamp cord, to the individual disks in the strings of insulators, by means of two wood handles. The readings would then be taken, whereupon the megger would be taken to the next tower, on which another pair of men were ready to go through the same procedure. With this arrangement about four towers per hour could be tested, each tower being provided with eighteen disks.

On a double-circuit line about 26 towers were covered in ten hours.

The following results were obtained:

On a total of 2100 disks under observation, 14 of this number were found defective.

Twelve disks had defects invisible from the ground, and in two disks the defects were visible from the ground.

Of the twelve invisible from the ground, two of these could be noted as defective from the tower, four could be detected by very close inspection, after taking down, and six showed absolutely no defect.

One of these disks, the defect of which was entirely invisible, measured 300 megohms, two measured 250 megohms, and the balance were less than five megohms, which was the lowest point on the scale. Good disks were considerably over 1000 megohms.

Insulator failures with reference to their location on line, and relation to ground wire:

On a 100-kv. line, protected by ground wire, of a total of 94 failures of disks, it was noted that 28 were on the top wire, 25 on the middle wire, and 40 on the bottom wire.

Insulator failures in reference to steel towers vs. wood poles:

Insulator failures were compared on the following basis:

100-kv. tower line..... 35,770 disks
Failures..... 94 "
(Wires arranged vertically, single and double circuit, one ground wire)

60-kv. tower lines..... 2440 disks
Failures..... 4 "
(Wires arranged horizontally, single circuit, one ground wire)

60-kv. wood pole line..... 14,850 disks
Failures..... 4 "
(Wires arranged on right triangle, single circuit, one ground wire)

60-kv. wood pole line, using pin type insulators. 5718 insulators
Failures..... 1 insulator
(Wires arranged in right triangle, single circuit, no ground wire.)

The suspension disks are 10-in. (25.4 cm.) corrugated, single piece porcelain. The pin types are four-part, 14 in. (35.5 cm.) diameter, 12½ in. (31.9 cm.) high.

In connection with these failures it should be noted that the 100-kv.

line is equipped with six disks per string and the operating voltage is between 95 and 100 kv. The 60-kv. lines have three disks per string and operate at from 60 to 65 kv. The pin type insulators operate at 60 to 62 kv.

Probably one-third of the failures on the 100-kv. line occurred when the line was dead and the two ends of the same grounded. Of the four failures, on the 60-kv. wood pole line, using suspension insulators, three of these occurred while the line was temporarily operating at 22,000 volts. The pin insulator failure occurred while the line was dead and all three wires grounded at one end. The question arises, after considering these failures, whether there is any use in having more disks than are required to give a reasonable factor of safety on insulators, and also whether wood crossarms on steel towers should not be seriously considered:

Next follows a report from a California company.

Regarding the experience of the Southern California Edison Company with high-tension transmission lines, this company built a transmission line of 70,000 volts and about 120 miles (193 km.) long.

The towers are of steel, and a pin type insulator was used, being 18 in. (45.6 cm.) in diameter. These insulators were carefully tested out in the factories in the East, and were of three different makes.

These insulators gave absolutely no trouble for a period of at least one year, and the only line trouble experienced was due to eagles grounding the wire to the steel towers. However, after the second year had passed we began to experience considerable puncturing of insulators, and a careful inspection disclosed many insulators which were honeycombed with minute cracks. The line was very carefully gone over, each insulator being struck with a piece of hickory wood; this being the method used in testing fine porcelain ware in the china shops. All defective insulators were carefully culled, every one not ringing true being at once removed. We sometimes found indications of cracks on the rim of the insulator, but as a rule on one or the other of the petticoats. During the past five years, I have brought this matter energetically to the attention of the porcelain manufacturers, and have always insisted that the porcelain of the insulator shows an apparent aging, the cause of which we have been unable as yet to determine. This may be due to the extreme changes of temperature, to the continual vibrations of the wire, or perhaps a combination of the two; at any rate the aging of these insulators is going on with increasing rapidity, and every inspection of the line means the finding of hundreds of defective insulators which were in good shape the year previous.

In changing these insulators over (which work is going on at present) all are being replaced, both good and bad, with the suspension type. We have endeavored to use a few of these large 18-in. (45.6 cm.) insulators on some of our local 33,000-volt lines, with the idea that they would be serviceable in sections where the salt from the sea rapidly encrusts them; but even at this low potential we have had many of them break down electrically, showing that the insulators which originally stood the test for 100,000 volts were rapidly becoming wholly unfit for any of the high-potential work.

Our experience with the suspension type insulator has been too limited

to warrant us in giving an opinion as to their superiority over the pin type, but on our 60,000-volt line, four insulators in series, extending from Long Beach to Colton, a distance of approximately 80 miles (128.7 km.), we have discovered a great many broken insulators; especially when used as strain insulators. These were evidently broken by extra mechanical strain, and showed no exterior indication of injury. We, however, are watching this very closely, and have gone to the expense of changing the sets of insulators, taking the old ones back to our laboratory for test. As stated above, there appears to be a continual aging of all porcelain insulators going on, and they seem to be short-lived. Whether this is due to the combination of electrical and mechanical strain, I am unable as yet to say.

The following report by another engineer is along the same lines.

Experiments in the method of eliminating defective insulator sections by tests of insulation resistance with a megger have been conducted on the 100-kv. lines of the Yadkin River Power Company in North Carolina and upon new insulators in Utah intended for erection on the 130-kv. lines of the Utah Power & Light Company.

The Yadkin River Power Company operates 96 miles (154.4 km.) of double-circuit 100-kv. line from the Blewett Falls generating station to Raleigh and connecting through to the Southern Power Company at Durham, and also a 56-mile (90.1 km.) single-circuit line from Blewett Falls to Lumberton. This latter line is supported in part by single-circuit towers and in part by double-circuit towers carrying also a 22-kv. circuit. The conductor is three-strand No. 1 B. & S. copper. There is one overhead grounded cable and the insulators consist of six 10-in. (25.4 cm.) disks of the usual type. This line traverses a district subject to lightning storms of unusual and even extraordinary severity. During the past summer, the first lightning season of the line's service, there have been numerous cases of insulator trouble. Nearly all of the trouble has been experienced over a short section of about six miles (9.6 km.) length. The section is in open country and contains no angles or special features of construction, and no explanation of its especial susceptibility is obvious except that the storms appear to be of greatest severity in this vicinity. Failures have occurred usually on insulators supporting the top or the bottom conductor. The top conductor changes to the bottom at a transposition point in this trouble section.

The failures have been almost all of the same character; a disk will be punctured through the head, inside of the cap, the puncturing will be accompanied by an explosion which will blow considerable porcelain from the cap, causing the disk to separate and allowing the line to drop. The disk usually affected is the lowest of the string.

The load at Lumberton is mainly cotton mill power and no power is taken on Saturday afternoon and Sunday. On Saturday and Sunday, August 16 and 17, megger tests were made of all of the disks on 28 towers, covering between three and four miles of the section which has been experiencing trouble.

On the 28 towers were 94 strings of six disks each, or 564 disks. The disks were tested one at a time. Thirteen disks or 2.3 per cent were

found to be defective, the 13 disks occurring in 12 strings. Of the 13 punctured disks, two would have been apparent from the ground, since the disks were broken; six could have been discovered by close inspection after climbing the tower, since there were cracks in the metal insulator cap; three could not have been observed from the tower but would be apparent after taking down the insulator; and in two cases the disks did not show any visible evidence of having been punctured, although the megger showed them to have no insulation value."

Although these tests were on a very small scale and there has been no subsequent opportunity for continuation of them, yet they indicate that frequently a string of insulators will fail gradually, one disk at a time, and that a considerable measure of protection may be secured by periodic elimination tests with a megger, provided lines may be taken from service for the tests.

In Utah experimental tests have just been started on insulators not yet erected. The first reported test was as follows:

A. 400 10-in. (25.4-cm.) disks were tested and found good.

B. 100 10-in. (25.4-cm.) disks of another make were tested and found good.

C. 264 pillar insulators each consisting of three 10-in. (25.4 cm.) disks were tested; 26 insulators contained one bad disk each and two contained two bad disks each, a total of 12 per cent bad insulators or 4 per cent bad disks.

The insulation resistance of the defective disks ranged from 550 megohms to a value below the scale of the megger, which was one megohm.

D. 12 pillar insulators of another make, each consisting of eight 14-in. (35.5-cm.) disks, were tested and one disk found bad. The insulation resistance of this disk was about 25 megohms.

The defective insulators had been subjected to a factory high-potential test before shipment.

Three of the low-resistance 10-in. (25.4-cm.) disks in the pillar insulators mentioned above were subjected to a high-potential test and all failed, although at such voltage values as to make it seem possible that some would have stood up for a considerable period in service before actually puncturing. In the case of two others of the low-resistance disks, the metal caps were drilled off, but no cracks or visible defects were found. In general, it seems probable that clean insulators which have the low values of insulation resistance noted above will not stand high-potential service, owing to the local heating which would inevitably result.

These Utah tests are being continued with a view to determining the advisability of making such tests of all of the insulators on hand before putting them into service.

It is planned to incorporate a megger test in the specifications for all future insulator orders.

At voltages around 110,000 and even somewhat higher, there seems to be no reason for providing protection for the end units of suspension insulator strings to equalize the voltage gradients over the whole. There will doubtless come a time, with higher

voltages, when such protection will be needed, and experiments have been made which demonstrate the efficiency of end shields for this purpose. These shields act simply as electrodes for equalizing the electrostatic field in the region occupied by the insulators. Shields should present smoothly rounded surfaces and edges and need be no greater than 12 to 14 in. (30.4 to 35.4 cm.) in diameter to produce good results. With these shields may be mounted arcing rings or tips to keep arcs away from the insulators, as found necessary.

Clamps and Fittings

There are several types of clamps on the market intended to secure the line conductors to suspension and strain type insulators. These all perform this function very well insofar as they do not allow the conductor to slip. Some are so severe, however, that the cable is mashed and unfit for taking strains if the sags ever have to be readjusted, by no means an uncommon occurrence. Practically none of the clamps are designed with smooth outlines or with an idea of avoiding more or less sharp projections which cause static discharges at the higher voltages and which concentrate the electrostatic field in that vicinity.

Notes on Station Apparatus

Rapid improvement has been made in the design and construction of transformers since the advent of the higher voltages. It was a comparatively simple matter to build a transformer for 60,000 volts which would stand up under all manner of severe service without ever giving any trouble, even when used with a large generating capacity back of it. Transformers built along the same general lines with more insulation were then tried at 110,000 volts, but trouble developed almost at once, sometimes through the short-circuiting between turns of the windings or else at tap points, and quite often by the distortion of the coils under short-circuit conditions. It was then recognized that because of their different physical constants, the higher voltage transformers were, so to speak, much more susceptible to line disturbances such as switching, etc., than those for lower voltage, and the designs have been changed accordingly, much attention being given especially to the bracing of the coils. The greatly improved results which have been obtained since these changes have been carried out, testify to the soundness of the principle of strengthening apparatus against failure rather than the spending of large sums on protective devices of various kinds.

An important problem for distribution companies serving sparsely settled districts, especially those in the West, is that of securing small high-voltage transformers, three-phase or single-phase, which will stand up under the line switching, surges, etc., which occur in ordinary operation of a large high-tension system. The companies must generally reach out for all possible load wherever it may be, and it is of prime importance that this subject of small high-tension transformers should receive the greatest possible consideration, as the services usually secured by their use pay the highest price for energy, making it possible for any company to extend its lines to be ready for the business as the country develops. Such transformers only, will make it possible to serve the farming community, which, it is claimed by some, offers the most attractive income now in view for operating companies, because of the fact that once the farmer is connected to the lines, he will remain a customer with increasing energy consumption, with good load factors, and furthermore, the general expense of service, such as collections, moving meters, etc., is very much reduced with this class of service, in contrast to the floating population of a great many cities.

Oil circuit breakers are becoming more reliable for high potentials and heavy service, but it is still unwise to attempt to rupture short circuits close to the generators when their combined normal capacity is much greater than 50,000 kw.

While it is generally believed that the electrolytic lightning arresters, as at present developed, are the best in their line that the art affords, it is still quite difficult to make any definite qualitative statements in respect to the protection they actually afford against lightning or other disturbances. Certainly no one would care to take the responsibility of operating stations without arresters, for they are considered to be a form of insurance against trouble; but it would be desirable to have more light on the subject.

Interferences with Telephone and Telegraph Lines

This is a subject which has been given but little attention, although the problem is a very important one. Nearby telephone and telegraph lines are sometimes made inoperative when any disturbance exists on the transmission line.

A good part of the trouble of the telephone service is due to insufficient insulation. Some of the lines, before long-distance

transmission was inaugurated, ran through and touched the branches of tree tops, which caused leakage in wet weather, and hence unbalanced the wires.

With the troubles due to poor insulation overcome and the transmission line well balanced, no further trouble was encountered except at times of disturbance or interruption on the transmission line. With grounded systems this resulted in the burning out of telegraph relays and blowing fuses on the telephones.

A much more difficult matter to deal with is the making of the transmission company's own private telephone to operate at all times. Usually the telephone line is needed the most at times of trouble and this is just the time when it is out of service, having been put out of commission by the trouble itself.

When providing protection for a recent telephone line paralleling a high-voltage system for a distance of some 300 miles (482.8 km.), it was found that there is no protective apparatus on the market capable of handling the large induced currents which are always present on such lines.

Thus the apparatus had to be built, and was of a very substantial character. The basic principle which was worked upon was to make the line subject, in the first place, to as little trouble as possible by carefully insulating and balancing it with respect to the transmission line circuits. This meant that transpositions had to be placed at frequent intervals. Furthermore, no twigs or other objects were allowed to come into contact with the wire. The usual grounding coils, but designed specially for this purpose, were cut in at each station. By these means alone the line was rendered quiet, even though within 60 ft. (18.2 m.) of the high-voltage wires, and conversation could be carried on over a distance of 125 miles (201 km.) with greater satisfaction than over the paralleling commercial circuits. Much heavier fuses were used, for it was not permissible to have them blow out when the circuits were needed most. Discharge gaps were provided, some of these being in vacuum, which gave very good results. The other protection consisted of condensers and choke coils for absorbing the smaller disturbances which would make conversation more or less unsatisfactory. It must not be understood, however, that any or all of these means can be guaranteed to produce a quiet working line, for each case must be studied by itself and methods adopted to meet the conditions.

APPENDIX I—DETERIORATION OF PORCELAIN INSULATORS IN SERVICE

BY J. A. BRUNDIGE

While it has been recognized practically since the inception of the electrical art that the commoner insulating materials, such as rubber and compound treated fabrics, are subject to more or less rapid destruction when under the influence of continued electrical stress, the more solid insulating bodies, like glass and porcelain, were looked upon as being permanent in their characteristics and it was considered that they could be relied upon indefinitely to perform their functions. This idea in the minds of engineers has persistently held, even though a few pioneers a number of years ago suggested that it was not impossible that glass and porcelain might be subject to a molecular fatigue when acted upon by electrical forces for long periods, similar to that exhibited by metals under repeated mechanical stresses. Now it is safe to assume that the majority of operating engineers, having to deal with higher voltage transmission lines, have had experiences which lead them to believe in the theory of electrical fatigue in porcelain. Whether this comes about solely through the continued application of the normal operating voltage or whether it is due to the transient overvoltages which are unavoidable on any line, is hard to say, but the existing evidence points to the latter conclusion.

It must not be understood that all or even the greater portion of the failures experienced with suspension type insulators are due to molecular deterioration of the porcelain. A large number of the failures have been traceable to improper design of the insulator parts or to an unsuitable porcelain body.

It has been the experience of a number of transmission companies to have practically no insulator trouble for the first couple of years of operation; then the insulators began to fail in increasingly greater numbers, for no apparent reason. Closer examination, however, sometimes revealed the fact that minute checks had formed all over the surface of the porcelain, and that the failure had been due to a crack extending clear through the shell. This behavior of the porcelain has not been confined to any kind or type of insulator nor to any one manufacturer's product.

The principal requisites for a good porcelain for high-voltage insulators, are high dielectric strength and mechanical toughness. These two qualities are somewhat opposed to each other

in the actual manufacture, for when a high dielectric strength is obtained, the porcelain is apt to be brittle like glass. It is possible, however, to arrive at mixtures which exhibit both properties to a marked extent when the firing has been properly done, although it is regrettable that some so-called high-voltage porcelains appear to be lacking in both of these properties.

This can be better understood when it is learned that the mixtures used by two prominent manufacturers, each putting out a product which is accepted as reasonably good, vary greatly in the proportion of ingredients employed. While the felspar contents of the two mixtures are of the same order, one has twice as much flint as the other, and the quantities of ball clay and china clay vary as much as three to one. Yet the different manufacturers regard their mixing formulas as trade secrets, and the proportions are religiously followed down to tenths of one per cent. This latter is doubtless done for the sake of uniformity of product, which is important, but until the mixtures more nearly approach a recognized standard, it appears that more or less trouble may be expected with high-tension insulators.

Doubtless, the factor having more to do with the failure of insulators than the porcelain body is the design; or in other words, not only must the electrical characteristics of the insulator, such as puncturing and flash-over values, both of which are highly important, be considered, but also the size and shape of the parts as well. With certain pin type insulators, especially those mounted on metal pins, cracks have been observed in quite a number of the petticoats. These were evidently expansion effects due to temperature changes. The same effects have been noticed to a greater extent with the suspension type insulators provided with metal caps and pins. We have here porcelain, cement and iron assembled together, the coefficients of temperature expansion of the three being quite dissimilar. In this latitude the temperature variation between summer and winter days is well in excess of 100 deg. fahr., and it can be appreciated that enormous internal strains must be set up inside of the caps. The porcelain being the least able to withstand these forces, is the part that suffers and cracks, with the attendant electrical punctures ensuing. In the case of an insulator designed for high mechanical strength in tension, which necessarily means a rather high cap with correspondingly long pin, the temperature changes cause a marked var-

iation in the length of the pin which is in contact with the porcelain through means of a layer of cement for a distance of sometimes 2½ to 3 in. (6.3 to 7.2 cm.) along its length. The great strain to which the porcelain is subjected is then apt to produce cracks perpendicular to the axis of the pin, which has actually been found to be the case in a large number of instances. These cracks, however, are mostly very minute and can hardly be detected by the eye if the cap and the cement have been carefully removed. A line of ink drawn over the surface of the porcelain, however, will nearly always disclose the cracks, as the ink will be drawn along them by capillary action.

The method of failure of suspension insulators with metal caps and pins is often quite characteristic. Cracks develop at some point inside the cap, and when the current leakage through them is sufficient, a path is fused through the porcelain by the intense heat generated. If the heating takes place relatively slowly, a hole is apt to be fused through the cap, through which gases and melted porcelain are forcibly expelled, but the insulator usually holds together and continues to support the cable. With a large amount of power back of the break, which may act in the nature of a short circuit inside the insulator, caps have been known actually to explode, in which event the line conductor is allowed to fall. Before the burning of the caps can take place, it is necessary that several of the units of an insulator string be bad, and instances have been observed where all the caps of ten-unit insulators have been so affected. With the better methods for locating cracks and faults as soon as they have developed, such as the high-range megger, the pyrotechnic displays above described have become fewer.

Because of several instances of trouble of this character having recently been observed in connection with suspension type insulators, some engineers have been led to believe that they are unsuccessful, which conclusion is wholly unwarranted.

The high-range megger has proved to be an extremely useful instrument for the locating of insulator faults undiscoverable so far as ordinary means of inspection are concerned. Tests made on a large number of units later checked up by tests with a high-tension transformer, have shown that the megger can be absolutely depended upon if reasonable care is used to see that there is no leakage in the conducting leads. To show the sensitiveness of the megger, the two electrodes can be placed within ¼ in. (6.3 mm.) of each other on a glazed porcelain sur-

face or upon a fractured surface where there is no glaze and the reading will be practically infinity. By blowing the breath upon this surface even when the porcelain is at a moderately high temperature, the moisture so deposited will be sufficient to give a comparatively low reading on the needle. When a crack occurs in the porcelain up inside the cap there is always sufficient moisture present in the cement to give an indication on the needle, which need not be confounded with surface leakage, if the insulator is at all reasonably clean. If the insulators are so dirty that surface leakage is marked, they should be cleaned before the megger test. Certain insulators may give a reading of from 40 to 100 megohms, and if later tested with a high-tension transformer they will not fail immediately upon the application of voltage, but may hold up until 30,000, 50,000 or even 60,000 volts is reached before puncturing. Those which show a zero reading on the megger will stand no voltage from the testing transformer.

An interesting experiment was recently made by immersing a batch of insulators in water at ordinary temperature and slowly bringing them up to the boiling point. Twenty insulators, some two or three years old, were tested in this manner and every one was found to be ruined by the time boiling point was reached. These were from two different manufacturers, one of whom has previously delivered batches of insulators where bringing them to the boiling point of water was one of the routine requirements before the insulators left the factory. Other similar tests made on new insulators of the same design did not produce failure, except in a few units. The probable explanation of this is that in the new insulators the cement had not yet attained its ultimate hardness, and allowed the expansion to take place in the pin without cracking the porcelain.

The data at hand upon insulator failures are unfortunately very incomplete, and until these are collected and have been studied, all designs brought forward must necessarily be lacking in some respect. Enough is already known, however, to indicate the general direction which the new designs will follow, and it may be confidently predicted that the troubles experienced will be materially lessened in the immediate future.

APPENDIX II—RADIUS OF INFLUENCE OF A DIRECT LIGHTNING STROKE

BY L. C. NICHOLSON

A lightning stroke to earth at some point adjacent to a high-tension transmission line induces voltages and frequencies in the transmission conductors of sufficient magnitude to affect the insulation of the line, causing either spill-overs or punctures of insulators. The question often arises as to how near the line lightning can strike without affecting its operation. The answer to this question can never be definite, since not only do transmission lines vary in degree of both insulation and lightning protection, but the character and severity of lightning strokes undoubtedly vary between wide limits. General atmospheric electrostatic conditions also have an effect.

Through continued personal inquiry it is possible to arrive at a general estimate concerning the radius of influence of a direct lightning stroke. By noting objects which have been struck by lightning adjacent to transmission lines and comparing the operation of the line at the time the object was probably struck, an opinion can be arrived at, which is applicable to a particular transmission line located in a given lightning belt. Such an opinion undoubtedly would have to be modified considerably to apply to transmission lines of different insulation characteristics and lightning protection and exposure.

Observation and inquiry lead to the following general conclusions on this subject.

1. It is doubtful if any degree of insulation in use at present, with or without the ordinary protective measures, will withstand the effect of a direct stroke of lightning on the line. In such a case the electromechanical forces acting on the porcelain are very high, usually causing insulators practically to explode. It is not unusual in such cases to find insulators shattered into small fragments, many of which are thrown as far as 100 ft. (30.4 m.) from the line. Furthermore, a direct stroke usually envelopes all the conductors of a line and sometimes envelopes several lines located relatively close together. This would indicate that the area of the stroke itself is large, or that it has numerous prongs. Observation of burn marks on conductors which were struck when there was no power on the line indicate by their distribution and extent that the diameter of the stroke was approximately 20 ft. (6 m.) Such being the case it is not surprising that one or more overhead ground wires cannot always intercept direct strokes.

2. Induced effects from strokes at some distance from the line may, on medium-voltage lines, be of sufficient magnitude to cause flash-over or puncture of insulators. Extended observation of the operation of 60,000-volt pin type insulators, unprotected by overhead wires, leads to the estimate that the radial influence of direct strokes is rarely in excess of 2000 ft. (609 m.) and may be less than 100 ft. (30.4 m.). These are rather wide limits, but the most definite evidence available indicates their probability. It appears that strokes of great severity, 2000 ft. (609 m.), and more in extreme cases, from the line, produce disturbances of operation, while strokes of less severity may occur at 100 ft. (30.4 m.) from the line without producing such results. These last are, however, in our opinion, rare, and a stroke at less than 2000 ft. (609 m.) from the line is apt to cause trouble.

In more highly insulated lines the danger zone apparently decreases substantially, and in the most highly insulated circuits at present in operation it is probable that the large majority of induced effects are insulated and protected against, leaving only direct strokes on the line itself to be taken.

Careful numerical tabulation of lightning effects indicates that direct strokes on the line constitute approximately 10 per cent of all lightning disturbances on 60,000-volt pin type circuits located in New York State.

APPENDIX III—TRANSMISSION LINE PROBLEMS IN THE WEST

BY P. M. DOWNING

The different power companies operating on the Pacific Coast have done a great deal in the way of pioneer work in the transmission of power over long distances at high voltages. This was due, to a considerable extent, to the fact that there is an abundance of water available for the hydroelectric generation of power, and also to the fact that the cost of fuel is very high as compared with that further east.

The first long-distance transmission to be put into successful operation on this coast, if not the first in the United States, was that of the San Antonio Light & Power Company in southern California, at what is known as their Pomona plant. This transmission was for a distance of 30 miles (48.2 km.) at 10,000 volts.

Transformers were at that time not manufactured for such high voltages, and it was necessary to connect in series ten 1000-volt transformers for stepping up. The low-tension windings were connected in multiple.

The first polyphase installation was made in 1893, at Mill Creek, and furnished power to the city of Redlands.

The success of these undertakings gave a great impetus to the hydroelectric industry, and inside the next five or six years, there were several different companies operating at voltages as high as 60,000.

The climatic conditions of the Pacific Coast, and particularly of California, are most favorable to the operation of high-voltage lines. Except in the higher mountain districts, there is practically no snow to contend with, and there are but very few places where lightning ever causes any trouble. Some operating companies have installed lightning arrester equipment, but it is not common practise to do so. The well-known horn gap arrester, one side of which is connected directly to ground without resistance, has in many instances been used to advantage, more as a voltage-limiting device than as a lightning arrester. These have proved quite satisfactory for this work. Ground wires strung above the line wires have been used to some extent, but there is so little trouble from lightning that engineers have never been able to decide as to whether or not there is any advantage in using them.

Very seldom, if ever, is it possible to find where an insulator has been punctured due to lightning. This is, possibly, due to the fact that the high voltage dissipates itself over the surface of the insulators. Many instances are known where lightning striking the line has burned off one or more wires between poles, and gone to ground without in any way damaging the insulators, and only slightly damaging the wood poles.

The greatest trouble on lines using the ordinary four-part, 14-in. (35.5 cm.) pin type insulators at voltages around 60,000 is that due to leakage over the insulator. The climate of this coast is peculiar in that there are two seasons, one being dry and lasting for six months, the other being wet. During the dry season, and particularly in the sections near the coast, dust and salt fog accumulates on the insulators to such an extent that leakage eventually burns off the pole, and sometimes the line wires, without damaging the insulators.

Different ways of overcoming this trouble have been tried.

Cleaning the insulators does some good, but does not entirely eliminate the trouble. After the first heavy rains come on in the early winter, the insulators are washed off and less trouble is experienced during the rainy season than at other times.

Ungrounded metal pins connected together electrically give very much less trouble than where they are not so connected, or where wood pins are used. Grounding the pins has been tried with unsatisfactory results because of arcing over the insulator. When once so established the arc will hold until the voltage drops.

The regulation of voltages on a high-tension network is not always an easy problem. No one particular point can be selected at which voltage can be kept constant, but it is necessary to keep it as nearly uniform as possible over the entire system. This is accomplished by the use of synchronous condensers located at the more important distributing centers.

These condenser regulators can be made automatic by using contact-making voltmeters, relay switches and motors to control the field rheostats; in other words, by the use of auxiliaries similar in every respect to those used in connection with the well known automatic induction regulator. A number of such installations have been in satisfactory operation for several years.

The first high-voltage oil switches were constructed and put into operation in California. The same general type and design that was originally selected as being suitable for 40,000 volts is, with slight modifications, still being used on 110,000-volt lines. In this particular switch the circuit is opened at two or four points, depending on the voltage and load carried. The contacts are made by rotating blades moving in a horizontal plane. The separate oil containers for each leg of the circuit are insulated from each other and from the ground by means of properly designed porcelain bushings or insulators.

Another very successful design of switch for the same character of service is that using a pantograph arrangement of links carrying contacts, thus giving a break in a vertical plane. Both of these types of switch have for years been in successful operation under all conditions of load. They have a weakness common to all oil switches, in that when operated under heavy short circuits they will at times throw oil out of the container.

Outdoor oil switches, either automatic or non-automatic, are being used very generally for branch lines, or for sectionalizing trunk lines. For economic reasons the automatic switches are

very often operated by means of a solenoid placed directly in the main line. Such an arrangement does away with the use of current transformers, but has the objection that the connection from the movable plunger to the relay, or trip, must stand the entire voltage from line to ground.

As the sensitiveness of the trip is, to a considerable extent, dependent upon the weight of the moving parts, the importance of keeping this weight down to a minimum is apparent. Well-treated rods of sufficient length have been used to make the connection from the plunger to the trip, or relay, but they have not been entirely satisfactory, because sooner or later the leakage burns them off.

Transformer designs have more than kept pace with the art of long-distance transmission at high voltages, and it is now possible to get satisfactory apparatus for any voltage that can be handled on the lines.

One thing, however, that some manufacturers have failed to give proper attention to is that of supporting the windings to prevent injury or distortion due to mechanical strains set up when short circuits occur. In units of large capacities and high voltages, the coils are generally built of strap copper, using one turn per layer, these turns being separated by one or more thicknesses of insulating material. Obviously, with such a construction, the turns will be easily displaced, unless they are well supported on both sides.

A number of failures have recently occurred where straight vertical separating strips have been used in assembling the coils, thus leaving the turns between these separating strips unsupported throughout their entire length, and allowing them to be displaced when short circuits came on. Shorter strips placed diagonally across the coils, or wave-shaped strips, which will allow a free circulation of oil, will entirely overcome this trouble.

APPENDIX IV—SWITCHING

BY G. FACCIOLI

Switching produces, in general, an abrupt change in the value of the electromotive force and of the current of the circuit, or of either of these quantities, and therefore it produces a sudden change in the amount of energy stored in the circuit, with the result that oscillations are produced.

The severity of these oscillations depends on the difference be-

tween the running conditions before and after the switching is done. For instance, if a dead line at zero potential is suddenly connected to an alternating-current generator, the oscillation produced will be most severe when the switch makes the connection at the instant at which the electromotive force has its maximum value. Likewise, if a short-circuited line is disconnected from an alternating-current generator, the oscillation is most severe when the circuit is broken at the instant at which the current passes through its maximum value.

The oscillations are of two kinds: They may occur between inductance massed at one point of the circuit, and capacity massed at another point of the circuit, as, for instance, when a dead line which acts practically as a condenser is connected to a generator which acts practically as an inductance, or when a line (capacity) connected at one end to a step-down transformer (inductance) is disconnected from the generating system.

They may also occur between the distributed inductance and capacity of a part of the circuit, as, for instance, when a line is disconnected from a generator and the energy stored in the line gradually dies out, changing from electromagnetic energy stored in the distributed inductance of the line, to electrostatic energy stored in the distributed capacity of the line and vice versa, or when an unloaded step-down transformer is disconnected from the line, its windings acting similarly to a line.

These oscillations do not, in general, constitute a great danger to the circuit if the contact in the switch is made once, positively, for every switching operation.

However, if each switching operation is accompanied by arcs, so that the circuit is repeatedly closed and opened, then the pressure rises may become dangerous, and destructive cumulative oscillations may be set up in the apparatus. Furthermore, at the instant at which contact is made, traveling waves are sent out from the point of switching along the line in both directions. These traveling waves with steep fronts follow, naturally, the well-known rules of reflection and refraction, and whenever they strike a localized oscillatory circuit, they excite in it oscillations at its natural period.

For instance, if a dead line is suddenly connected to a live line having the same constants, a "wave of charge," equal in value to one-half of the potential of the live line, starts along the dead line from the switching point. If the dead line is open at the far end, the "wave of charge" is reflected back at double

potential, etc., etc. At the same time a "wave of discharge" starts along the live line from the switching point with a value equal to one-half of the original voltage of this line. If the live line is connected at its origin to transformers, this "wave of discharge" is reflected back with double voltage and may excite local oscillations in the transformer windings or in the circuits of the power house, etc., etc.

These traveling waves are a source of danger and obviously the danger is increased when sparking and arcing occur in the switch.

It is seen from the above that high-tension switching, which has lately gained so much importance in the art, should be done very judiciously and only when necessary, unless special precautions are taken to avoid the disturbances resulting therefrom.

As a rule, low-tension switching is preferable, as this avoids steep wave front phenomena.

For instance, in energizing a line, it is preferable to connect the dead line to the dead step-up transformer and then connect, by low-tension switches, the line and transformer to the generator, rather than connecting the transformer alone to the generator and then switching the line onto the high-tension winding of the transformer. Of course, in this case it would be still better to connect the line and the step-up transformer and the generator together while the whole system is dead and then bring it up gradually to full potential by the excitation of the generator.

Fuses act similarly to switches, except that the former open under load, while switches are, as a rule, operated at approximately no-load. The sudden interruption of large amounts of current results in considerable over-tensions, and this is the danger that usually accompanies the blowing of fuses.

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PRACTICAL OPERATION OF SUSPENSION INSULATORS

BY H. W. BUCK

ABSTRACT OF PAPER

The paper describes some of the mechanical and electrical problems which have been experienced on high-voltage transmission lines equipped with suspension insulators and points out some of the principles involved and some practical methods for guarding against the troubles. Figures are given showing the deflections which will take place, for various sizes of aluminum and copper conductors, at the insulators, under the pressure of maximum probable wind velocity.

THE APPLICATION of suspension insulators to high-voltage transmission lines, since their first introduction in 1905, has been very general on all lines operating at voltages over 50,000, and the results obtained have been in most cases very satisfactory. The change, however, from the rigid pin insulator to a construction involving the free and flexible suspension of the conductor in space is a radical one and the change in practise has taken place with considerable abruptness, so that it is not surprising to have experienced a new class of line troubles. It is the purpose of this paper to point out a few of the difficulties which have been experienced, with the hope that a discussion of the subject may lead to improved standards of construction for such lines.

In the pin insulator line the conductor is held rigidly at every insulator, consequently lateral and longitudinal movement of the conductor is resisted at every point of support. Suspension insulators, however, except at dead-end connections, are free to move in all directions. The result is that high winds occasionally cause displacements which are electrically and mechanically dangerous to the operation of the line. Deflections of suspension insulators from the vertical position result also from other causes, which will be discussed later.

Large angular deflections of suspension insulators require large clearance spaces, which necessitate long crossarms and increased cost of tower. Consequently it is desirable to limit the deflection as far as possible. A 60-deg. angle from the ver-

tical is assumed to be the maximum allowable under extreme conditions.

In order to show how nearly the above limitation can be attained in practise, Table I is given, indicating the deflections caused by wind pressure on various sizes of conductor, at the insulator. The wind pressure assumed in the table is 15 lb. (6.8 kg.) per sq. ft. (0.09 m.) of projected conductor area, which is taken as the maximum. Wind pressure deflections are practically independent of span length, since wind pressure per span and the force which resists the wind pressure, namely, the weight of the conductor, both vary directly with length, in the same proportion.

TABLE I

A Size conductor	B Wind pressure	C Angular deflection	D Auxiliary weight
	STRANDED	COPPER	
4	15 lb.	66 deg.	0.041 lb.
3	15 "	63 "	0.028 "
2	15 "	60 "	0.0 "
1	15 "	58 "	0.0 "
0	15 "	55 "	0.0 "
00	15 "	52 "	0.0 "
000	15 "	49 "	0.0 "
0000	15 "	45 "	0.0 "
	STRANDED	ALUMINUM	
2	15 lb.	81 deg.	0.156 lb.
1	15 "	79 "	0.161 "
0	15 "	78 "	0.171 "
00	15 "	77 "	0.182 "
000	15 "	75 "	0.186 "
0000	15 "	74 "	0.196 "
250000	15 "	72 "	0.190 "
300000	15 "	71 "	0.177 "
400000	15 "	68 "	0.158 "
500000	15 "	66 "	0.125 "

Experiments have shown that the weight of the string of suspension insulators themselves will not act to resist wind displacement of conductor, since the exposed surface of the insulators is sufficient to cause their deflection by wind pressure without the attachment of the conductor. Neither will the deflection vary appreciably with the size and design of the insulators, since a heavier insulator ordinarily exposes a larger "sail area." The wind displacement of conductor can therefore be assumed to be independent of the number of insulators in the string, and of their particular design.

Table I indicates approximately the wind deflections which will take place for various sizes of conductor under a stress of wind equal to 15 lb. per sq.ft., as above. Two tabulations are given, one for copper, and the other for aluminum.

In Table I, column A shows the conductor size in B. & S. gage. Column B gives the assumed wind pressure in pounds per square foot of projected cable area. Column C gives the angular deflection of the insulator from the vertical, due to the assumed wind pressure on the conductor, assuming that the insulator itself deflects independently and neither increases nor decreases the displacement of the conductor. Column D shows the amount by which the weight of the conductor would have to be increased in order to reduce the deflection of the insulator under the assumed conditions to within the 60-deg. limit.

It will be seen from an inspection of the table that all sizes of copper except the smallest sizes listed, namely, No. 4 and No. 3, will ballast the insulators sufficiently to keep the wind deflection down to within 60 deg. A line of No. 4 B. and S. wire, it will be noted, is deficient in weight to the extent of 0.041 lb. per ft. and No. 3, 0.028 lb. per foot.

On the other hand, all the sizes of aluminum cable listed will allow deflections in excess of 60 deg., and especially among the smaller sizes, objectionable displacements will occur. Under these conditions one of the chief supposed advantages of aluminum, namely, its lightness, becomes its disadvantage, and the actual ballasting quality of copper due to its higher specific gravity and smaller size is a distinct advantage.

The larger sizes of conductor are more stable mechanically against wind deflection, since their weight in proportion to the surface exposed to wind is greater than in the small sizes, the weight increasing as the square of the diameter, whereas the wind pressure is only directly proportional to the diameter.

Fig. 1 shows a method for reducing deflection which has been adopted on an aluminum transmission line in the South, about 200 miles (321.8 km.) in length, which has produced satisfactory results. The line is of No. 0 B. & S. aluminum cable, with an average span length of about 300 ft. (91.4 m.). An auxiliary weight made of cast iron is attached to the lower side of the suspension clamp at every insulator. It is consequently placed at a point where it is most effective as ballast. This arrangement results in very satisfactory stability of the line under all conditions.

Column D, Table I, shows the auxiliary weight which must be added at each insulator for the proper stability, expressed in pounds per foot of span. In the opinion of the writer, auxiliary weights of this kind should be provided on all aluminum lines using suspension insulators and on all lines where the smaller sizes of copper are installed. The auxiliary weight not only stabilizes the line against wind pressure but improves its operation in many ways, such as in resisting longitudinal movement of insulators under unbalanced pull due to a breakage somewhere along the line. It also improves conditions where a gust of wind strikes a single span independently, in reducing the slack which can be taken from adjacent spans due to unbalanced pressure.

A curious and unusual phenomenon has been experienced on at least one suspension insulator transmission line known to the writer, and is illustrated in Fig. 2. A severe sleet storm had occurred along the line during the night and all the conductors were covered with a heavy coating of sleet. When the sun came out in the morning the sleet started to melt, but it did not, naturally, fall off all spans of the conductors simultaneously. The condition illustrated in Fig. 2 occurred. Sleet has melted and dropped off spans B_1 and B_3, leaving span B_2 loaded and all other conductors in normal position, either sleet-covered or otherwise. Span B_2 will then sag down, taking slack from adjacent spans, and will come in contact with conductor C_3, causing a short circuit. Such a combination of circumstances, although unusual, might happen on any suspension insulator line where the conductors are disposed in the vertical plane, and should be guarded against.

On long tangents on a suspension insulator line where there are no dead-end connections installed, if a very high wind strikes the line at an angle of about 45 deg., cumulative waves like the waves on the surface of the water have been observed to travel along the conductors of the line, causing a whipping action at all suspension insulators, the waves finally "breaking" as on a beach at the first dead-end connection met. This phenomenon cannot occur on a pin insulator line, since the line is confined at every crossarm. This trouble can be prevented by dead-ending the line at frequent intervals.

The methods of dead-ending suspension insulator lines as at present practised cannot be considered satisfactory. There is a wide margin for improvement in the design of the mechan-

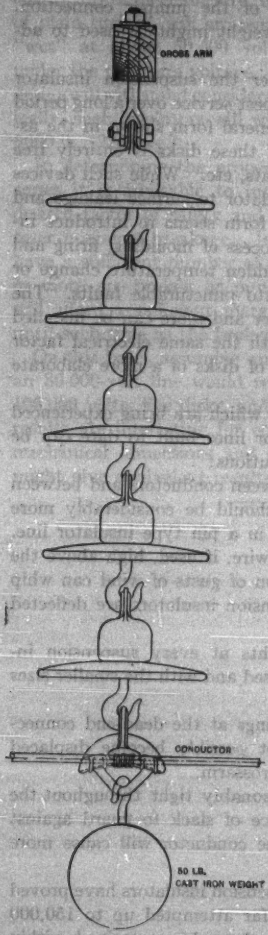
CROSS ARM
CONDUCTOR
50 LB.
CAST IRON WEIGHT

FIG. 1

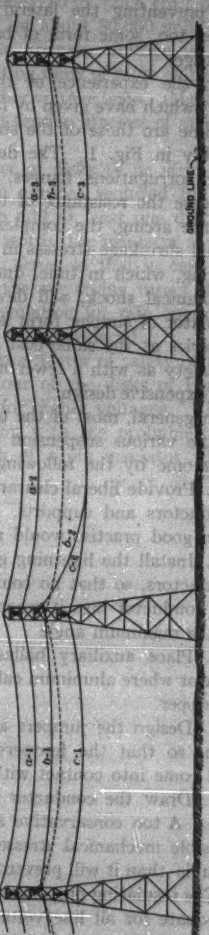
GROUND LINE
a-3
b-3
c-3
a-2
b-2
c-2
a-1
b-1
c-1

FIG. 2

ical fittings used for the purpose, especially in providing means for preventing the lateral swing of the jumper connection. Here, too, some form of ballast weight might be used to advantage.

In the experience of the writer the suspension insulator units which have given by far the best service over a long period of time are those of the simple general form shown in the assembly in Fig. 1. The design of these disks is entirely free from corrugations, flanges, petticoats, etc. While such devices increase the resistance of the insulator to surface leakage and surface arcing, the complexity of form seems to introduce internal shrinkage stresses in the process of moulding, firing and cooling, which in time, due to sudden temperature change or mechanical shock, will develop into puncturable faults. The insulator of simpler form is cheaper and more can be installed in series at the same cost and with the same electrical factor of safety as with a fewer number of disks of a more elaborate and expensive design.

In general, most of the troubles which are being experienced in the various suspension insulator lines built to date can be overcome by the following precautions:

1. Provide liberal clearance between conductors and between conductors and supports. This should be considerably more than good practise would require in a pin type insulator line.

2. Install the lightning ground wire, if used, high above the conductors, so that no combination of gusts of wind can whip the conductor into it when suspension insulators are deflected to the maximum angle.

3. Place auxiliary ballast weights at every suspension insulator where aluminum cable is used and with the smaller sizes of copper.

4. Design the jumpers and fittings at the dead-end connections so that the jumpers cannot possibly become displaced and come into contact with the crossarm.

5. Draw the conductor up reasonably tight throughout the line. A too conservative allowance of slack to guard against possible mechanical stresses in the conductor will cause more trouble than it will prevent.

The insulating properties of suspension insulators have proved adequate for all line voltages so far attempted up to 150,000 volts, and the satisfactory results have been attained within reasonable mechanical dimensions of insulators. The insulating

units shown in Fig. 1, which are about as small as any made, electrically or mechanically, being merely 10 in. (25.4 cm.) disks of plain surface, will arc over "dry" at about 80,000 volts and "wet" at about 50,000 volts. The arc-over voltage is well under the puncture voltage. Insulating units of more elaborate design will withstand considerably higher voltage tests. Mechanically, such insulators will withstand tension stresses of at least 5000 lb. (2268 kg.)

In determining the proper number of disks to be strung in series it is advisable to install the number required for the desired factor of safety and then to add at least one disk for reserve against breakage. In other words, the insulator should have a sufficient number of disks in series so that in case one or more are broken or punctured the remaining intact disks will afford a sufficient margin of insulation for safe operation until such time as the broken disks can be replaced.

On this basis, assuming an insulation factor of safety of two, an 80,000-volt line would require four of the disks of Fig. 1, 100,000 volts, five disks, and so on for higher voltages. These results are interesting for comparison with the probable cost, mechanical dimensions and strength of a pin insulator which might give equivalent results.

DISCUSSION ON SUB-COMMITTEE REPORT ON "PROBLEMS OF HIGH-TENSION TRANSMISSION LINES" (SOTHMAN AND OTHERS), AND "PRACTICAL OPERATION OF SUSPENSION INSULATORS" (BUCK), NEW YORK, FEBRUARY 26, 1914.

H. W. Buck: I want to corroborate what has been said in regard to the sag table. It is one of those engineering problems which are worked out in the office in accordance with certain theoretical laws which are apt to be more or less disregarded in the field. There are many such phases in engineering, and there are some good reasons for disregarding the exact science of such deductions in field work. A sag table is worked out usually for level country, with a few cases given as exceptions to apply to certain typical points on the line where the profile varies from level. With a line crew out in the mountains under severe stress of weather, working as best they may, possibly at low temperature and with high winds, it is absolutely impossible to get construction men to pay attention to such refinements as are usually given in sag table calculations.

The point of this is that we should not rely too much on theoretical data of this sort. We should give our instructions in such form and should make our designs with sufficient margin so that results can come within the scope of action of the average construction crew, and not make the operating success of a transmission line dependent upon the fulfilment of all of the exact theory exemplified in a sag table.

F. W. Peek, Jr.: It requires a certain energy concentration to rupture insulation, break down insulators, etc. Such energy concentration may result when sudden changes are made in the stored energy of the system. These sudden changes may result from internal conditions or by energy impressed from external sources, such as lightning. The results during such changes are called transients. In modern high-voltage engineering the term "transient" has become a common and important word.

In order that energy may be transmitted from one point to another point to be utilized as useful work, energy must be stored in the space surrounding the conductors, in two forms—dielectric and magnetic. Energy is stored in the dielectric circuit with increasing voltage and delivered back with decreasing voltage. Energy is stored in the magnetic circuit with increasing current and delivered back with decreasing current. With transients, as with all electrical phenomena, there are three constants with which the engineer must deal: with resistance, which causes the absorption of energy somewhat analogous to friction; with capacity and inductance, which act as energy storage reservoirs.

The energy stored in the magnetic field is

$$\frac{i^2 L}{2}$$

The energy stored in the dielectric field is

$$\frac{e^2 C}{2}$$

When the current is zero, all of the energy is stored in the dielectric.

If i is suddenly changed, after a given time the circuit gradually assumes a new e and i. The transient occurs between the initial and final values of i. During this time energy is transferred from one form to another at a given definite frequency called the natural period of the circuit:

$$f = \frac{1}{4\pi\sqrt{LC}}$$

The resistance of the circuit acts as a damper and gradually dissipates this energy.

For example: suppose a switch is suddenly opened when all of the energy is stored magnetically. i is suddenly reduced to zero. The energy must be changed to dielectric energy or the voltage must first be increased to a sufficient extent to store this energy in the capacity; thus e becomes

$$\frac{e^2 C}{2} = \frac{i^2 L}{2}$$

$$e = i\sqrt{\frac{L}{C}} = iZ'$$

The term $\sqrt{\frac{L}{C}}$ thus acts somewhat as in impedance and for this reason is called "surge impedance." When energy changes from one form to another in this way at regular time intervals and no energy is transferred along the circuit, it is called a "free oscillation." The oscillation continues until the energy is dissipated by the resistance.

When an oscillation is impressed upon a circuit which has no definite relation to its natural period, it is called a "forced oscillation."

If electrical energy from some external source—such as lightning—is suddenly impressed upon a transmission circuit, it travels along the circuit with the velocity of light and it is called a "traveling wave." The energy stored magnetically is equal to the energy stored dielectrically. The traveling wave may thus be thought of as being made up of a voltage wave and a current wave in phase.

In a standing wave the voltage and current are at 90 deg. (and not in phase as in the traveling wave), as in this case no ene gy transfer takes place.

These various transient phenomena are all subject, to a certain extent, to calculation, but experimental work is necessary to

determine their cause and the means for their suppression. The effects may be quite different, depending upon the apparatus. For instance, low-voltage high-frequency forced oscillations may be impressed upon a circuit without damage, except in certain apparatus containing inductance and capacity, where very high local over-voltages may be built up. A single impulse of very steep wave front may be applied to an insulator. The voltage of this impulse may be many times the 60-cycle puncture voltage of the insulator. Flash-over results. During the flash-over, which requires a very small but definite time to start, this insulator is strained and small local cracks may result. A sufficient number of these impulses will cause breakdown of the insulation. If two gaps of differently shaped electrodes are spaced so as to spark over at 100 kv. at 60 cycles, and these gaps are then placed in parallel and an impulse of steep wave front is applied, discharge will take place across one gap and not the other, even though the non-sparking gap is greatly decreased in length. The voltage is high enough to spark over either gap. It therefore goes over the gap requiring the least time to rupture. It may be interesting to note that a traveling wave 1000 ft. (305 m.) long passes a given point on a transmission line in approximately one millionth of a second. It can be seen that the experimental problem is a difficult one.

From the protection standpoint, oscillations must be absorbed and dissipated by resistance or the wave front of traveling waves modified by the two other circuit constants.

Spectacular "high-frequency" tests blindly made on apparatus are barbarous. Tests of this sort should never be made unles thoroughly understood. Rupture does not take place at a lower voltage at high frequency (where heating does not result) but generally a higher voltage is required to accomplish the same destruction in the limited time. Damage results from the enormous local concentration of voltage.

Certain phenomena which always exist go unnoticed in engineering until the energy involved becomes great enough to make them problems. The turning-point may be quite sudden, and it often appears as if new and mysterious factors enter. Such, in a way, was the case of corona on transmission lines. Up to 80,000 volts or so the conductors were sufficiently large so that dielectric flux concentration was not great enough to cause rupture. In order to keep the same amount of copper and transmit greater energy, the voltages were increased. This increase of voltage was just sufficient to bring the dielectric flux density past the rupturing point. Corona phenomena changed from those of a few brush discharges at rough points on the conductors to complete breakdown of the air around the conductors. Corona thus became a problem, and the laws of corona loss were determined. A similar turning-point has just been passed in solid insulation. The insulation problem has changed from a mechanical problem to a problem of the dielectric circuit.

Charles E. Waddell: I am inclined to think a right-of-way easement is to be preferred to ownership in fee. Usually an easement is cheaper to acquire; and when containing a proviso for ample clearing of timber an easement will serve every purpose. The length of the span determines the width for timber clearance, and while the right-of-way strip may itself be of inconsiderable width it may be very necessary to clear high standing timber to quite a distance from the line, as high winds frequently blow the line far out of plane.

As to the question of grounded steel towers versus wooden supports, I confess that at the present stat of the art I am leaning back toward wooden pole construction with wooden arms and non-grounded fittings. I have in mind a line where a steel tower line is paralleled by a wooden pole line, both 60,000 volts, from the same transformers. The wooden pole line is of standard, conventional crossarm construction, with pin type insulators. The steel tower line is equipped with suspension insulators. The interruptions on the suspension insulator line have been too numerous to count, while the wooden pole line has yet to have its first interruption.

A point brought out by Mr. Buck is the question of line ballasting and the effect of swinging of insulators. It seems to me that it is desirable to suspend the insulators so that they have infinite latitude to swing with the line, making a hinge for that purpose, but that the movements across the line be restricted to the lost motion in the joints themselves. With a wind blowing across the line, the swinging is restricted to the individual span, —the line as a whole is not deflected outward. This prevents a wave starting that may ultimately end in the line rotating, with the result in some cases of wrapping the conductor around the ground wire.

I heartily agree with Mr. Buck as to the wisdom of using a number of small, single-piece, inexpensive disk insulators. I believe these are to be preferred to the use of the two-part insulator with its greater surface and greater first cost.

I cannot say that I agree with Mr. Buck on the subject of ballasting the line, however. It seems to me it might be a very excellent desideratum where some emergency condition had to be met, but in designing new work I think that a lower voltage and larger wire, a more carefully graded line, and closer tower or pole spacing, would meet the same ends without introducing the added weight on structures and stresses on the insulators.

Reference was made in Mr. Brundige's paper to the fatigue of porcelain. I want to suggest that this fatigue, perhaps, is not due alone to the electrical stresses, but to a combination of electrical and mechanical stresses. The majority of insulators strung up and sustaining only their own weight successfully withstand laboratory test for flash-over and puncture. The same strings of insulators when placed on the line and supporting the weight of the conductor, which may be 1000 lb. (453 kg.) or

more, break down under a very slight rise in voltage. The only conclusion I have been able to reach in the matter is, that, due to some obscure phenomenon, the dielectric strength of the insulators is weakened, and that if the mechanical stresses were removed the insulation would in all probability be as high as when actually tested.

Of the types of conductor mentioned in the committee's report, the one that particularly appeals to me is the steel-cored aluminum. I built an experimental line of this material in 1910. The line was seven miles (11.3 km.) long and of three conductors, equivalent in carrying capacity to No. 0 copper. The wire had a breaking stress, I believe, of some 6000 lb. (2720 kg.), and an elastic limit of some 4000 lb. (1815 kg.). The cables were drawn with a dynamometer to about one-fourth the ultimate strength; approximately 1500 lb. (680 kg.) The topography of this particular line indicated that some such conductor was best suited to the particular need. The spans varied from approximately 200 ft. to 2400 ft. (61 to 730 m.).

I have had this line under critical and constant observation since it was built, and have no fault to find with it whatever. Due to bad judgment on my part, the wires were placed too close together, and the high winds have occasionally swung them together; and when the burn is sufficient to fuse the aluminum, it is found that the steel core sustains the strain, and further, that the aluminum under the stress unwraps and frays, making it easy to locate the place by observation from the ground.

Another reason for using it, a reason which I think is a good one, is that, assuming the life of the cable is short, say twenty years for example, the saving over the cost of copper for such a line is ten per cent to fifteen per cent; and if the line is completely destroyed within the twenty years, the material has justified its use.

Percy H. Thomas: The most important topic brought up, it seems to me, is the matter of the so-called deterioration of porcelain. It has developed to a critical point during the last year in many different parts of the country and with many different kinds and makes of insulators. The deterioration has developed, sometimes, where it could not possibly be due to electrical causes; and sometimes it is an open question whether it is not due to electrical causes. The problem is to find out what it is, and how to overcome it.

I think we can conclude that it is not due to the deterioration of porcelain *per se*, for, taking the worst cases of breakdown of insulators, there are many insulators which are, apparently, absolutely uninjured, and moreover, in any which are injured, much material is good. It is, in my opinion, therefore not a deterioration of the porcelain *per se*. It is, further, not always due to the presence of electrical potential. I think that in all probability a great deal of the deterioration is due to things that happen during the processes of manufacture. When you remember that the material at one time is in a plastic state,

and that when it is burned it has to shrink into a semi-crystalline mass, keeping every portion intact, you can see that, during the forming, the pressing and the twisting it gets, somewhere on the interior there may very readily occur a slight plane of weakness or an actual separation. The edges may be daubed over and adhere, yet this fault will never be corrected. There may be enough good porcelain to hold the potential during the test, while the insulator is new, before the faults develop, but after repeated heating and cooling or strains produced by expansion of other parts, there may be further development of the mechanical fault. I think the evidence of the general situation points to this conclusion.

You cannot exactly blame the manufacturers for it, as they are doing the best they can, and there is no one manufacturer who has all the trouble. It is a problem which we must work out with time, and meanwhile we must find some way of detecting the bad insulators. That can partly be done by tests, but we need a few new tests.

If we can assume that the difficulties in high-tension insulators are, most of them, due to defects depending upon the history of the individual insulator, that immediately puts a premium on the two-piece insulator with two shells independently made, and put together. For if one shell is defective there will not be, in all probability, another defective shell along with the first. But with the two-piece insulator the flash-over voltage should be so low that a single piece of porcelain will be sufficient to withstand the full strain and prevent a puncture. If reliance is placed on one shell when the other is injured, that shell alone must be able to take care of the flash-over. This double-piece insulator has a great advantage, considering incidental mechanical strains, in that, if due to expansion, or heavy stress, there is a small check on the inner petticoat, due to mechanical reasons, there still remains the outer shell intact. The mechanical strains on the outer shell are far less, on account of the larger dimensions.

R. J. McClelland: As to tower specifications, I am thoroughly in agreement that in all tower calculations the figured ultimate strength of the structure should be determined by the elastic limit of the steel; also that at least one of each type of tower should be tested to failure and the working loads for which the tower is to be used checked against the actual ultimate strength.

With regard to the term "factor of safety," I am of the opinion that the use of this term as applied to a transmission line tower, as a whole structure, is misleading and should be abandoned, and that the term "margin of safety" should be adopted in its stead. The term "factor of safety" should be used then only with reference to the unit stresses of the individual members of the structure.

The term "margin of safety" indicates the relative excess strength of the built-up structure, and has no direct relation to the unit stresses in the members.

When writing specifications for towers one should consider the specified test loads as being practically the ultimate strength of the structure. The working loads should then be specified with an ample margin of safety, and these working loads should be put in the specifications for field use, instead of the test loads. In this way, the tendency of the construction men to consider the tower good for all loads that do not exceed test loads will be avoided.

With regard to tower footings, it would be valuable to receive data from various engineers as to the comparison of steel footings in earth with similar footings encased in concrete. In some earths and localities a standard type of concrete footing can be installed as cheaply as a safe earth footing and gives much better construction, while in other situations the earth footing is amply safe and much cheaper. In the case of towers with concrete footings, I consider it well to make a substantial earth connection. This is a feature that has been neglected on many of the earlier lines.

It would be valuable to possess reliable data on the action of alkaline soils on steel or concrete tower footings and on the effectiveness of concrete waterproofing methods, either integral or external, in preventing this action. When earth footings are used in acid or alkali soils, we would recommend protection of the stubs either by the application of coal tar or other suitable paint for perhaps two feet (60 cm.) below and one foot (30 cm.) above ground level, or by a concrete sleeve cast in a hinged sheet steel or other form, covering the same portion of the steel stub. Both methods leave the towers well grounded through the steel grillage of stubs and provide additional protection at the point where corrosion is likely to be most active.

Taking up the question of the arrangement of conductors, with regard to the "staggering" of conductors in vertical arrangement, it would be interesting to learn from the engineers who have used the extended middle arm construction if this has given the desired freedom from "sleet jump" troubles. Has it been proved that 2 to 3 ft. (60 to 91 cm.) horizontal offset in a span of over 1000 ft. (305 m.) gives satisfactory operating conditions at voltages of 60 kv. and over?

For protection against severe wind conditions only, the vertical arrangement of conductors is the better, whereas the horizontal arrangement of conductors is better for protection against sleet troubles.

In some recent 110-kv. construction, an interesting expedient has been used to guard against excessive sag produced in one span due to unequal distribution of sleet over the adjacent spans. At every third or fourth suspension tower a special "semi-tension" insulator construction is used; that is, instead of one single string of insulators in suspension which allows the conductor to move in the direction of the line, as much as 14 in. (35 cm.) in the case of extreme uneven sleet load, two strings have been

used, attached to the tower at an angle of 45 deg. like an inverted V. Under normal conditions a tower with this construction is practically a suspension tower, and the conductor runs straight through without a sudden change in direction, such as occurs at a tower equipped with tension insulators and a jumper; but whenever unequal sleet loading takes place, the tendency of the heavily loaded span is to rob the adjacent spans of their sag, and this is opposed by one of the "semi-tension" strings acting more as a tension insulator. I understand that sand-bag loading tests have indicated this construction to be effective and the application of this idea might prove of benefit for existing lines in the heavy sleet territories. This installation will be watched with interest.

It may be noted that I have used the term "tension insulator" in place of the usual "strain insulator," as the former designation would seem more closely descriptive of the actual working conditions of the insulator.

As to railroad and telephone crossings, during the past year we have installed a modified type of crossing protection on our lines in various parts of the country, that has met with the approval of the railroads and the signal companies. This construction consists of two parallel strings of standard suspension insulators spaced 15 in. (38 cm.) apart in the direction of the line, suspended from the ends of a Z bar rigidly secured at right angles to the axis of the crossarm, and the suspension clamps positively spaced at the conductor end by a malleable cast iron bar; the latter serves as the clamping piece in both suspension clamps, and has projecting ends which act as arcing tips. Standard towers designed for use with either suspension or tension insulators are used at each end of the crossing span, this span being somewhat reduced in length compared with the normal span. The main considerations leading to the adoption of this construction were as follows:

(1) That of increasing the safety of the crossing span by the use of an extra string of suspension insulators to support the conductor in case of mechanical failure of one string.

(2) The elimination of tension insulators, which, in our opinion, do not increase the safety of the crossing span as regards the falling of conductor, and are, moreover an extra hazard to the operation of the line.

(3) The desire to obtain satisfactory results without going into elaborate constructions, which in themselves are frequently more of a hazard than otherwise.

It is the experience of our companies that a large proportion of troubles originates from insulator failures rather than from mechanical failure of the conductors, and in this double suspension construction we have worked on the principle of increasing the margin of safety in the insulators supporting the conductor.

With the rapid advance into higher transmission voltage the present crossing specifications providing the same construction for all voltages of 5000 or over have become inadequate

to meet all the conditions involved, and in order to cover logically the wide range embraced there seems to be a distinct demand for subdividing into at least two classes, perhaps at about 15,000 volts. This would require a separate complete specification embodying simpler, but effective, types of construction for the lower or distributing voltages, and another specification suitable for the higher or transmission voltages.

Concerning transmission line hardware, for all heavy service I have found it desirable to eliminate malleable cast iron hardware, and it would be well if structural or pressed steel fittings, or mild steel castings, were developed for this service, on account of the increased reliability that would be obtained thereby.

On certain recent double-circuit tower line construction our company has equipped both suspension and tension clamps of all insulator strings of one circuit with discharge horns, leaving the other circuit with discharge horns on tension clamps only. It will be interesting to compare the performance of these two circuits in service.

V. Karapetoff: I wish to take exception to the statement No. 5, in Mr. Buck's paper, where he says, "Draw the conductor up tight throughout the line. A too conservative allowance of slack to guard against possible mechanical stresses in the conductor will cause more trouble than it will prevent." I am afraid this statement, coming from such an authority as Mr. Buck, will cause us more trouble than it will prevent. Several cases came to my attention not long ago where considerable trouble was caused by the conductor being drawn too tight, without reference to the stresses in the winter or during high winds. By interviewing the line superintendents, I found out that it is difficult to force the construction gangs and the foreman to conform to the tables of sags and also to use the dynamometer where the sag is determined by sighting the line. I wish very much that Mr. Buck would modify his statement so as to remove the impression that he does not believe at all in the correct calculation of sags and stresses, but simply advises us to draw up the lines as tight as possible.

P. M. Lincoln: Mr. Faccioli does not approve of switching on the high-tension sides of lines. Personally, I must say that I do not agree entirely with that position. Practically, I have never seen any bad effects from switching on the high-tension side, and theoretically I have always taken this position, namely, that although I am ready to admit that switching on the high-tension side does give rise to surges, these surges which it gives rise to are so small, compared to the surges which come from other operations, particularly from lightning, that if the apparatus is not capable of withstanding all the surges which arise from high-tension switching it surely will not stand the surges which arise from lightning.

I would like to make a statement in regard to the point just raised by Mr. Karapetoff. I am inclined to believe that Mr.

Buck is quite correct in the way he puts it. I do not believe that any great difficulties are to be anticipated from drawing lines too tight. I think the tendency is in the other direction—to allow them to become too loose. If a line is put up too tight and cold weather comes along, it may possibly strain the material of the line above the elastic limit, but what is going to happen if it does? It simply stretches a little, and when the warm weather comes along the stretch will result in a little more sag than before, but to stretch the material of the line above the elastic limit is not necessarily going to hurt the material. The material, in the course of its manufacture, has been strained above its elastic limit continuously, and if it is strained above the elastic limit after it is in service it is not by any means fatal to the line.

Farley Osgood: I think the manufacturers of our various lines of materials are doing about all that can be expected of them in the way of investigation for improvement. I do not think that the operating engineers, as a whole, are doing their share of investigating work. I think that it is up to the operating engineers to plan to spend sufficient money for proper testing schemes and devices, in order to help the manufacturers and designing engineers in the field, so that they can test in actual practise.

A point which has brought this matter vividly to my mind within the year has been our own considerable expenditure toward the investigation of the effect of high frequencies on the insulators and lines, and we found that insulators which had behaved reasonably well, as we thought, broke down very quickly under our high-frequency test.

Mr. Faccioli brought out clearly that the difficulties from voltage can be reasonably well cared for, and the difficulties from short circuits can be reasonably well cared for, particularly by means of reactance, but I do not agree with him at all that we should keep away from frequent switching. It cannot be done, in a complicated, busy territory. In our large power stations, with a heavy service, we will switch, for one cause and another, twenty to sixty times a day. It cannot be stopped. It has to be done. The engineers have to meet these conditions. I entirely agree with Mr. Lincoln that if the apparatus will not meet the service requirements it must be made to.

In my opinion, the difficulties from high frequencies are not well enough understood. The reason they have not been given careful study previously is because we have been so busy eliminating the difficulties from short circuits, high pressures, etc. Having cared for these, we can now take up the study of the effects of high frequencies. If we had done this before, many of our present difficulties would not have been known to us.

J. A. Sandford, Jr.: Mr. Brundige has suggested that engineers put into every insulator specification a description of the materials to be used. I do not believe that is a possibility. I had occasion to look up not long ago the chemical analysis

as laid down for what we call ball clay, or kaolin, from Kentucky, North Carolina, Georgia, one or two places in England, and one in France. You could lay these in a row here on this table and label them, and then take the labels off, and change them around, and you would never know which applied to which, they are so nearly the same. The great difference between the various clays used seems to be in their plasticity, but no one can tell what plasticity is or what causes it. Therefore, I think Mr. Brundige's suggestion would prove impracticable, particularly at the present time, with our limited knowledge of such things.

Second, on the question of fatigue of porcelain. I think that if a piece of porcelain is absolutely vitrified there is absolutely no fatigue. To my mind, what has been called fatigue of porcelain is simply the gradual giving way of porcelain that, in the first place, was not perfect, either through flaws, or from the vitrification standpoint.

To refer to a different matter, I think that a large percentage of the insulator failures on transmission lines would have been eliminated if, every time the patrolman went out to change an insulator—this has reference particularly to suspension type insulator lines—he had taken down the complete string of insulators and substituted a complete string of new insulators which he was sure were good. If you go out and look at a string of insulators on which you know there is trouble, there may be two or three disks that you can see are no good, and there may be two or three that look as if they are all right, and they may or may not be so.

There is one point Mr. Sothman brought up today, which was referred to here last winter, which I would mention again now, and that is the desirability of having at some place or other a laboratory where just and accurate comparative work on insulators and other similar devices can be done. The insulator manufacturers have done, as some one has said, about all they can do. It seems to me if the plan of having such a central testing laboratory could be carried out, either with or without the sanction of the Institute, it would be a great thing.

E. R. Albrecht: I notice in Mr. Sothman's paper, "Problems of High-Tension Transmission Lines," the following statement, relative to the crossing of high-tension lines—"There is at present no generally recognized type of crossing protection."

Did not the High-Tension Committee of 1911, together with the committee appointed by the National Electric Light Association, the American Electric Railway Association, and the Association of Railway Telegraph Superintendents, prepare Specifications for Overhead Crossings of Electric Light and Power Lines, which were accepted by the various associations?

Have these specifications still the approval of the Institute? Do they not cover the recognized type of crossing protection? If they do, why did not Mr. Sothman mention them? If not, what parts should be superseded, and by what?

The installation of proper crossing protection constitutes a part of my duties, and I am very much interested to know just how the Institute as a whole regards the specifications mentioned, and also, if the present High-Tension Committee recommend their use, and if not, whether they have any plans for revising them.

William L. Puffer: I am very much interested in what has been said concerning the life, deterioration of and failure of the several types of insulators in common use, because of an investigation of mine into the cause of undue leakage over the busbar cell-work and insulations of a moderately high tension station.

In this station it was known that there was some kind of ground or similar trouble, because at times tiny sparks had been noted at the heads of bolts and washers used in assembling the insulating slabs, and several disagreeable shocks had been received by attendants. As soon as possible a section was cut out of service and the parts dismantled, and to my surprise there was found a large collection of wet green paste on the copper bolts and studs. Chemical examination proved the presence of nitric acid, water, nitrate of copper and several sub-nitrates. The surface of the porcelains and all pores and cracks were wet with nitric acid of sufficient strength to destroy organic washers that had been used to distribute the pressure between the porcelain and the clamping nuts and bolts.

Further examination proved the presence of nitric acid in the cracks of both wet and dry process porcelain bushings, on the surface of the insulating coverings of the busbar cables and on the porcelain bushings used to support the cables where they passed through walls and barrier.

I was able to prove that all of the trouble originated in the small air spaces where the potential gradient was high enough to produce light and minute sparks of the type called "static". First there was produced ozone, then nitric acid and then action on the copper with the formation of nitrates. Similar action was found about some iron washers and bolts used in the construction of switches and the switchboard.

These results were not a matter of conjecture but of actual chemical proof obtained while the parts were alive and carrying current, and it certainly suggests that if a 6600-13,200-volt system can be subject to as great action as I found, there is ample room for thought as to what must be the conditions around the insulating parts of the highest tension lines now in use.

Whenever and wherever an insulating support shows a glow with little sparks in it there is likely to be the formation of ozone, and if a little moisture is present there will next be nitric acid. The wind may blow it all away, or a porous porcelain may slowly absorb it, with gradually lessening resistance, leading finally to a puncture and a short-circuit.

Ernest V. Pannell: Mr. Sothman's suggestion as to the establishment of constants to cover the commercial properties

of aluminum and copper is one well worth acting upon, and it would afford the manufacturer some idea of what he would have to work on and would give the engineer figures upon which to base his calculations. At present there is no recognized standard for these properties, and specifications are different all along. In particular reference to aluminum, the specification of elastic limit should have some reference to the size of the wire, as I have found on test that the elastic limit varies from 10,000 up to 20,000 with decrease in the gage. The new German rules, it is interesting to note, do not specify elastic limit for conductor material, but only elasticity, and give a maximum figure of 10,000 lb. per square inch for the stress in aluminum. This latter practise is to be deprecated, as it does not offer the same encouragement to the manufacturer to produce material of extra high grade as when the working tension is specified at so much per cent on the elastic limit.

Of methods and charts for determining tension and sag we have had rather a plethora, and if the Institute were to standardize one set of curves for both copper and aluminum, the result would be worth the trouble expended. The *Verein Deutscher Elektrotechniker* went into this subject very thoroughly last year and their recently published hand-book of standards for overhead lines is a model of conciseness.

Regarding steel reinforcement for aluminum cables, the British manufacturers do not view this practise with disfavor so much as being an unnecessary innovation. We can point to spans in Europe of 700 ft. (213 m.) and up to 2000 ft. (610 m.) being run by aluminum without steel centers, so there does not appear to be any crying need for reinforcement where the highest possible grade of aluminum is used. A composite cable made up of two materials, one of which has three times the specific extension of the other, seems to add just a little unnecessary complexity.

Julian C. Smith: I think operating men who have had experience in operating transmission lines of 50,000 volts and upwards, with pin type insulators, realize there has been a decided deterioration in the pin type insulators. The fact that it is easier to find the deterioration in the suspension type insulator, easier to replace the defective parts, would by no means indicate that the suspension type, *per se*, is any worse than the pin type. This is the more evident when you consider that practically all suspension type insulators are operating with one end grounded, whereas a relatively small number of pin type insulators subjected to the same voltage, are operating under these conditions.

There is one point in Mr. Buck's paper to which I take exception, and that is the number of units which would be put on very important transmission lines. It seems to me that the number of units should be fixed by the climatic conditions or local conditions rather than the operating voltage.

E. A. Lof: Mr. Sothman suggested that the clearance between the transmission wires and the ground should be in a cer-

tain relation to the transmission voltage. So far as I can see, this has nothing to do with the voltage, whether it is 50,000 or 150,000 volts. We must string the wires high enough to protect human life and to allow certain vehicles to pass underneath.

I would like to get Mr. Sothman's views on the necessity of grounding steel towers when provided with concrete foundations, and his views on the mounting of grounded wires on wooden poles. If the ground wire is not grounded at every pole, should it be supported on an insulator there, and if so, for what voltage should it be insulated?

C. O. Mailloux: One of our distinguished members, Cavv. Ing. Guido Semenza, of Milan, Local Honorary Secretary of the A. I. E. E. for Italy, has recently published a comprehensive set of charts containing in graphical form all the information needed for running overhead lines; *i.e.*, giving the sags and stresses that occur in overhead conductors of different sizes, in spans of different lengths, at all temperatures, and under all conditions of extra loading due to ice and wind. By means of these charts all determinations of sags and stresses for any set of conditions can be made in most simple manner by the man in charge of the work of constructing the line. It is probable that an English edition of this work will be brought out before long.

E. M. Hewlett: Mr. Buck has explained that if an insulator is designed with a petticoat so short that the flash-over point is much lower than the puncture point, normally, under both dry and wet conditions, the insulator will be less severely strained and will not be subject to as rapid deterioration as has been shown by some of the insulators used now. A number of the recent insulators have too great a diameter of petticoat, so the flash-over is too close to the puncture voltage.

Then, again, if you insulate your line for lightning conditions, as suggested by one of the last speakers, it will also be necessary to protect or insulate the transformers, lightning arresters, switches and everything else for the same conditions. This is a most important consideration.

Also, in the matter of mechanical strength, the distortion in design of the insulator to give great strength often works against the electrical characteristics. You thus handicap yourself when you ask for strength greater than is required.

In reference to the fatigue of porcelain, I have not seen the proof that well-vitrified porcelain undergoes fatigue, unless overstrained. From anything we have seen so far, I believe that what is known as fatiguing is largely the result of flaw of some description or of incomplete vitrification. That is, when not properly vitrified, the insulators will eventually absorb moisture. The glaze will protect the insulator for a time, but gradually deteriorates and then absorption through the porcelain begins and the unbaked porcelain gradually absorbs moisture and breaks down.

H. W. Buck: I am glad that Dr. Karapetoff has raised the question covered by Paragraph 5 in the conclusions at the end

of my paper, for it offers an opportuntity to accentuate the point which I desired to cover in this paragraph. Most transmission lines are too slack, and during the past year reports have come in from all parts of the country giving instances of short circuits resulting from conductors swinging together under wind stress, even where liberal clearances were allowed between conductors.

It has become customary to assume a heavy loading of sleet and the simultaneous action of wind velocities up to 100 miles (161 km.) per hour, allowing slack for these conditions, and then in addition to throw in a little for good luck. On top of all this slack, after the line has been in service for a few months the natural stretch which takes place in all conductor materials before a condition of permanent set has been established, still further increases the sag of the spans. The result of this is that many transmission lines are a series of festoons between tower supports, with all the lack of inherent stability which such a condition gives rise to.

I cannot see any reason for modifying this statement in regard to drawing the wires up tight, unless by supplementing it with a statement that the towers must be made strong enough to withstand the strain. The first line of the paragraph in question should of course be read in connection with the following three lines, which qualify it, I believe, sufficiently.

K. C. Randall: Mr. Rushmore has pointed out that insulators have not been developed along the lines of exact science

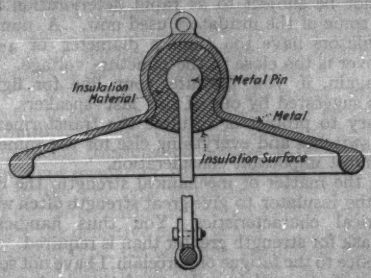

FIG. 1

like other pieces of electrical apparatus. This comment seems to be well founded so far as the average commercial insulator is concerned.

During the past five years considerable investigation on the proper design of insulation has been carried on, in the course of which the influence of shape as well as dimensions has been better understood. As a striking illustration of this, the In-

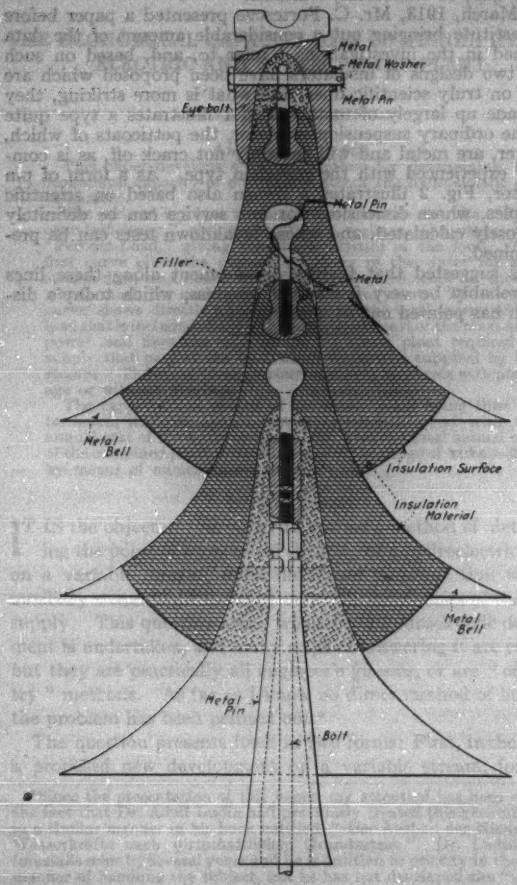
Metal
Metal Washer
Metal Pin
Eye bolt
Metal Pin
Filler
Metal
Metal Bell
Insulation Surface
Insulation Material
Metal Bell
Metal Pin
Bolt

FIG. 2

stitute is considering the standardization of a spherical or ball gap, because of its dependability, as a successor to the previous needle gap, so notoriously variable.

In March, 1913, Mr. C. Fortescue presented a paper before the Institute bringing out a considerable amount of the data obtained in the investigations I refer to, and, based on such data, two designs of insulators have been proposed which are based on truly scientific lines, and what is more striking, they are made up largely of metal. Fig. 1 illustrates a type quite like the ordinary suspension insulator, the petticoats of which, however, are metal and will certainly not crack off, as is commonly experienced with the porcelain type. As a form of pin insulator, Fig. 2 illustrates a design also based on scientific principles, whose dimensions for any service can be definitely and closely calculated, and whose breakdown tests can be predetermined.

It is suggested that further development along these lines will probably be very fruitful of progress, which today's discussion has pointed out as much needed.

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THE ECONOMICAL CAPACITY OF A COMBINED HYDRO-ELECTRIC AND STEAM POWER PLANT

BY CARY T. HUTCHINSON

ABSTRACT OF PAPER

This paper develops a general method for determining the economical capacity of a combined steam and hydroelectric development.

The method involves the use of two curves—one, the "Percent-Deficiency," giving the stream regimen, the other, the "Percent-Load," giving the characteristics of the load. The first curve gives the percent-deficiency of the water for any stream-flow, and hence fixes directly the deficiency in energy which must be made up by the steam plant. The second curve shows directly the proportion of the total energy of the load that is included above any proportional part of the maximum power, and fixes the capacity of the steam plant required to supply that part of the load which cannot be supplied by the stream. The use of these two curves differs for plants with pondage or without pondage.

The capacity and output of the steam plant being thus determined, its total annual cost is determinable and with the annual cost of the hydroelectric plant, fixes the total annual cost of the combined plant. This is done for the range of stream-flow by means of numerical examples.

INTRODUCTORY

IT IS the object of this paper to outline a method of determining the point of economical capacity of a hydroelectric plant on a variable stream, when developed in connection with an auxiliary steam plant to supplement the deficiencies of the water supply. This question arises whenever a hydroelectric development is undertaken, and many ways of answering it are current; but they are practically all engineer's guesses, or are "cut-and-try" methods. As far as I know no direct method of handling the problem has been pointed out.*

The question presents itself in two forms: First, in the case of a proposed new development on a variable stream, for what

*Since the presentation of this paper, my attention has been called to the fact that Dr. Adolf Ludin had previously treated this general subject in a similar manner in his book entitled, "Der Ausbau der Niederdruck-Wasserkräfte nach wirtschaftlichen Grundsatzen." Dr. Ludin's work forestalls mine by several years and he is entitled to priority in the general manner of handling the subject, but he has not developed the "percent-load curve" with the theorems attached to it, as I do on pages 168—et seq. This is the only novel element in my paper; the remainder is simply a new use of old material, such as the well known "duration" and "deficiency" curves.—C. H. T.

stream-flow shall the development be made? Second, assuming a plant already in operation, to what extent shall an auxiliary supply be provided in order to convert the "variable" supply into a "continuous" supply? Both cases involve a determination of the total annual cost of an auxiliary supply adequate to supplement the deficiency in stream-flow. In one case, the selling price of the combined hydraulic and auxiliary supply is to be determined and the development fixed for such stream flow that at this price the supply can be sold, in the given market. In the second case, the question is the determination of the cost of the auxiliary supply for various degrees of insurance and the comparison of this cost with the additional earnings that can be obtained from the sale of a "continuous" supply as compared with a "variable" supply. The two cases really merge into one, since both involve the determination of the total annual cost of the auxiliary supply, under the prevailing conditions of the power load and for the hydraulic characteristics of the particular stream.

In the case of a new project, the cost to build the hydraulic development per kilowatt is less as its capacity is increased, since a large proportion of the total cost is practically independent of the capacity of the equipment. In this case, an increase in the annual cost per kilowatt of the auxiliary steam plant is accompanied by a decrease in the annual cost of the hydraulic plant, and a point may be reached at which the sum of the two is a minimum. This would fix the most economical capacity of the development and hence the point of greatest profit for a given market price of energy. But it does not follow that it may not be desirable to develop the plant for a greater output, even if the profit per kilowatt is less. The limit to the development will, in all cases, be that at which all profit disappears.

The crux of the matter then is the determination of the cost of the auxiliary supply (hereafter referred to as the "steam" supply, although the argument is the same for any other kind of auxiliary plant) for the hydraulic characteristics of the stream in question, and as applied to the particular conditions of power load prevailing in the market in question. As a solution of this problem, I have devised a new form in which to present the hydraulic characteristics of the stream, which I call the "percent-deficiency" curve, and a new form in which to present the characteristics of the load, which I call the "percent-load" curve. The use of these two curves, the one summarizing the stream-flow data, the other the conditions of the load, makes

the determination of the total cost of the steam supply for any conditions of load, for any particular stream, a simple matter.

It may be worth while to call attention to the many assumptions that are made by engineers and others in the determination of the stream-flow for which a development shall be made. Some of the criteria that have been used are given in Table I, which shows various data of the Susquehanna River at McCall Ferry, for the period of twenty years from 1891 to 1910.

TABLE I.

SUSQUEHANNA RIVER AT MCCALL FERRY FOR 20 YEARS, 1891-1910. DRAINAGE AREA 26,000 SQ. MILES.

Basis of Flow	Sec.-ft.	Relative Flow
1. Lowest day in the period	2,200	1.00
2. Average for lowest week in the period	2,800	1.28
3. Average of the two lowest 7-day periods in each year, for 7 years (1904–1910)	6,300	2.87
4. Average flow for the lowest week of the lowest month of the six highest months for each year of the period (1904–1910)	20,000	9.10
5. Average of annual one-day minima	5,200	2.37
6. Nine-months flow for lowest year	5,400	2.45
7. Six-months flow for lowest year	12,000	5.48
8. Nine-months flow for average year	12,000	5.48
9. Six-months flow for average year	25,000	11.40

The differences in the choice of the basic stream-flow are great, bringing out clearly the fact that they are little more than guesswork; all are obviously deficient, inasmuch as they leave out of consideration the market for power. It needs no argument to prove that where power can be sold at a high price and conditions are favorable, the development can be carried to a higher point of stream-flow than where the opposite conditions prevail. Referring to the Table: No. 1, the absolute minimum, may be called the banker's or layman's criterion; it is this that the engineer is often confronted with, and has to explain away. Nos. 3 and 4 are assumptions of a basis of estimating power by a bureau of the Federal Government; the others are engineer's guesses.

Putting guesses aside, the determination of the question depends upon two principal factors:

1. The hydraulic characteristics of the development, and
2. The characteristics of the power market.

The treatment of the hydraulic problem is different in the case

of (a) hydraulic plants with pondage, and of (b) hydraulic plants without pondage. With pondage, the hydraulic energy during the periods of low stream-flow should be used to supply the peak-load, as far down as possible; on the other hand, without pondage, the hydraulic energy should be used to supply the base-load, during the periods of low stream-flow; in both cases the hydraulic energy is thereby utilized most advantageously.

By pondage is meant only sufficient reservoir capacity to permit using the daily inflow of the stream at any rate of outflow from the water wheels; that is, it assumes regulation of daily load only, and does not extend to weekly or seasonal regulation.

Regimen of the Stream

The fundamental data of stream-flow are usually given in the form of the hydrograph, Fig. 1; the ordinate gives stream flow and the abscissa the days of the year; the area of the curve up to any point gives the total run-off up to that point. From the hydrograph, Fig. 1, is deduced in the usual way, the "Duration" curve, Fig. 4, giving the different values of stream-flow from Fig. 1 arranged in order of magnitude, without regard to calendar order; the resulting curve shows the number of days in the year, regardless of order, for which the stream-flow does not exceed any particular value.

Fig. 1 gives the hydrograph for the Susquehanna for the year 1896, which chances to represent very closely the average regimen of the 20 years, 1891-1910. Fig. 2 gives for the same year, the low discharges, such as would be useful for a power-development; all flows greater than 1.0 sec-ft. per sq. mi. are omitted from this figure. Fig. 3 gives the low discharges for 1909, the lowest year; from these hydrographs the duration curves of Fig. 4 for the years 1909 and 1896 are deduced.

The duration curves of Fig. 4 are very irregular and are of little use in this particular form. If the curve for a certain year must be used, a smooth curve should be drawn representing as closely as may be the stepped curve of Fig. 4. The inherent uncertainty in gage readings and measurements of stream-flow makes it probable that a smooth curve drawn through the points will represent the actual conditions fully as well as the stepped curve itself.

The duration curves of Fig. 4 as well as all the hydrographs used as illustrations are for the Susquehanna at McCall Ferry where the drainage area is approximately 26,000 sq. mi. The stream-flow has in all cases been reduced to flow per sq. mi.

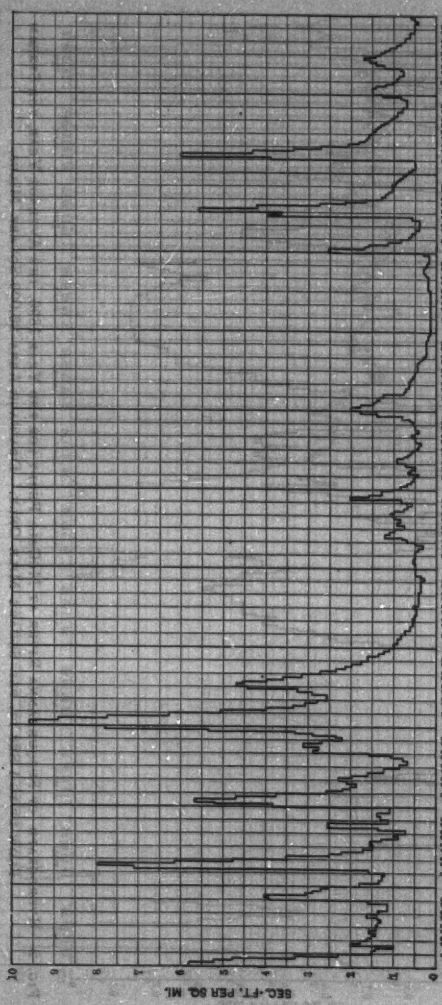

FIG. 1—HYDROGRAPH OF SUSQUEHANNA RIVER AT MCCALL FERRY FOR THE YEAR 1896, REPRESENTING THE AVERAGE YEAR. DRAINAGE AREA, 26,000 SQUARE MILES.

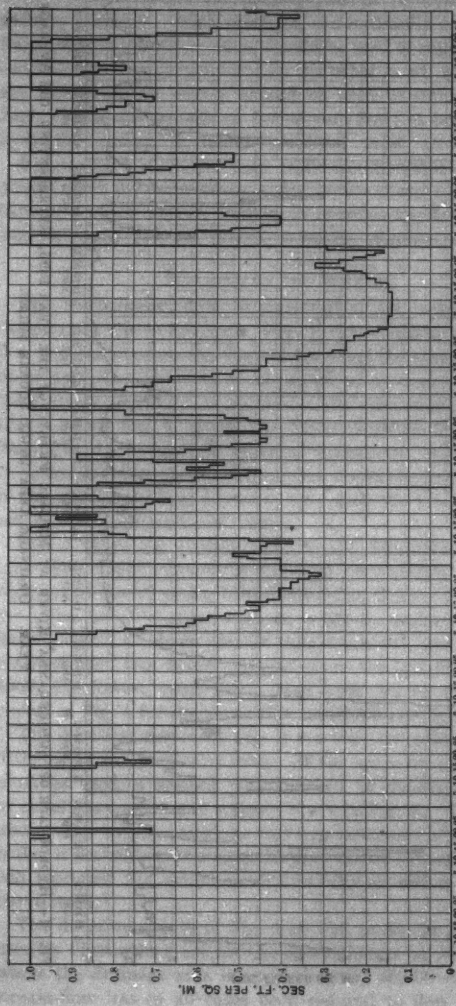

FIG. 2.—HYDROGRAPH OF SUSQUEHANNA RIVER AT MCCALL FERRY FOR THE YEAR 1896, THE AVERAGE YEAR, FOR STREAM FLOW UP TO 1 SEC-FT. PER SQUARE MILE ONLY. DRAINAGE AREA 26,000 SQUARE MILES.

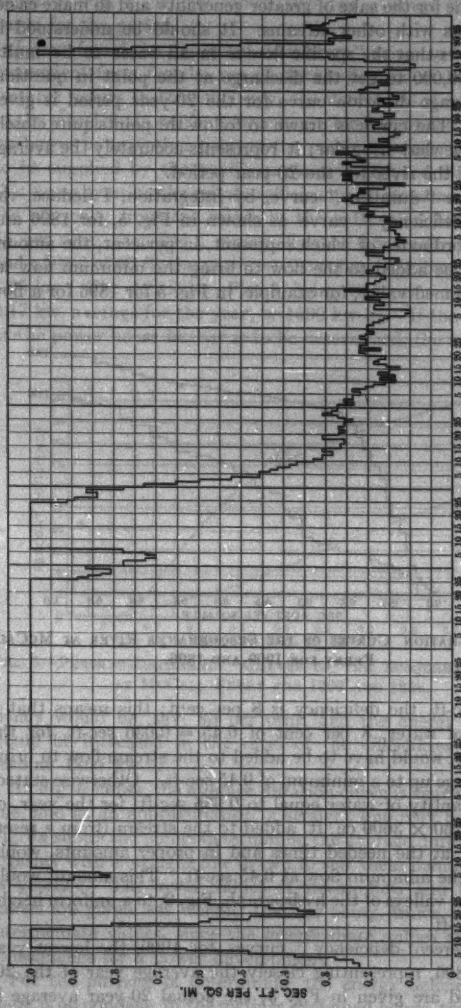

FIG. 3—HYDROGRAPH OF SUSQUEHANNA RIVER AT MCCALL FERRY FOR THE YEAR 1900, THE LOWEST YEAR, FOR STREAM FLOW UP TO 1 SEC-FT. PER SQUARE MILE ONLY. DRAINAGE AREA 26,000 SQUARE MILES.

This is done for the sake of greater generality and to make easier comparisons with other streams. It should be understood in what follows that the specific flow is in all cases to be multiplied by 26,000 to get the discharge at the point in question.

The average duration curve for the 20-year period is given in Fig. 6. The curve is drawn to follow the points quite closely and is somewhat irregular; it represents accurately the average regimen of the river for the 20-year period.

From the "duration" curve, by integration, I deduce the "percent-deficiency" curve as shown in Fig. 5, for 1896 and 1909, the ordinates of which represent, in per cent, the amount that must be added to the flow to bring the minimum flow up to any assumed value; for example, in Fig. 5 for 1896 for a flow

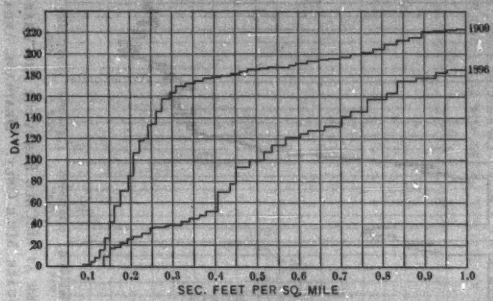

FIG. 4—DURATION CURVES OF THE SUSQUEHANNA RIVER AT MCCALL FERRY FOR 1909 AND 1896.

of 0.45 sec-ft. the deficiency is 8 per cent; this means that a quantity of water, 8 per cent of 0.45 = 0.036 sec-ft. for the entire year, would have to be added to the stream-flow to bring the discharge up to a minimum of 0.45 sec-ft. Otherwise stated, a total quantity of water equal to 0.036 sec-ft. for the year, or 0.036 × 8760 × 3600 cu. ft. added to the stream (from a reservoir, say,) at the needed times and in proper amounts, would maintain the minimum flow at 0.45 sec-ft. This amount would level up the valleys of the hydrograph, Fig. 2, to a uniform height of 0.45 sec-ft.

The "percent-deficiency" curves for 1909, the lowest year and for 1896, representing closely the average year of the 20-year period are given in Fig. 5; the actual 20-year average is

given in Fig. 6, which shows also the average "duration" curve for the period.

I have found the "percent-deficiency" curve to be the most convenient form for the use of stream-flow data; by assigning suitable values to the efficiency, the deficiency can be referred to the wheel shaft, to the power house busbar, to the substation busbar or to any other point of the power system. The energy to be supplied by the auxiliary plant is deduced directly from this curve by using the suitable efficiency; as, for example, assume the efficiency from the water to the substation busbar to be 65 per cent, then for a stream flow of 0.5 sec-ft. per sq. mi. and a head of 60 ft. the power at the substation busbar will be 1.65 kw. The deficiency, Fig. 6, being 10.4 per cent will equal 0.17 kw. average for the year, or 1500 kw-hr. If the deficiency at the power house busbar is to be determined, the correct effi-

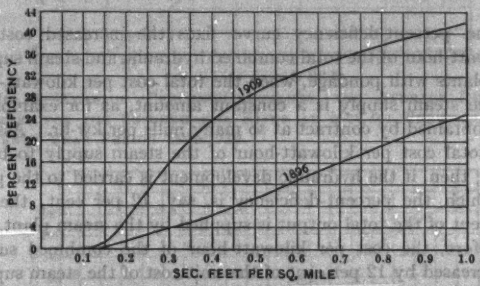

FIG. 5—PERCENT-DEFICIENCY CURVES OF THE SUSQUEHANNA RIVER AT MCCALL FERRY FOR 1909 AND 1896.

ciency would be, say, 80 per cent, and the energy deficiency would be increased in the ratio of the efficiencies and would become 1850 kw-hr.

As Fig. 6 shows, the average duration curve is nearly a straight line, and as an approximation, a straight line may be assumed. Fig. 6A shows the points determining the average duration curve, together with a straight line drawn to suit these points as closely as possible. The lower values of stream-flow and the higher values are given less weight, the line being drawn through the intermediate values, since the intermediate values are of more consequence for a power development.

For the purpose of determining the energy deficiency when there is no pondage, in the manner explained below, this approxi-

mation is sufficient. In all cases where the approximation will suffice, the deficiency in stream-flow, is calculated as follows:

Let

Q = any stream-flow.
Q_0 = minimum stream-flow.
D = days from duration curve.
d = a constant,—the number of days required to increase the flow by one sec-ft.

Then

$$Q = Q_0 + D/d \tag{1}$$

and percent-deficiency $= 100 \dfrac{Q-Q_0}{2} . D/365\,Q$

$$= \frac{1}{7.3}\left\{1 - \frac{Q_0}{Q}\right\} D \tag{2}$$

The percent-deficiency curve fixes the increased cost per kilowatt-hour of the total combined hydraulic and steam supply, for plants with pondage, when the total cost per kilowatt-hour of the steam supply is a constant amount, as for example, if it is obtained by contract at so many mills per kw-hr. Assume the total cost per kilowatt-hour of the steam supply to be 10 mills; then, if the hydraulic development is carried to the point at which the percent-deficiency is, say, 12 per cent, then 12 per cent of the total output is supplied by the steam plant, and therefore, the cost per kilowatt-hour of the combined supply is increased by 12 per cent of the unit cost of the steam supply.

This is sufficiently obvious, inasmuch as the added annual expense, on account of the steam plant, is equal to 12 per cent of the total output multiplied by the cost per kilowatt-hour of the steam supply. In other words, the steam supply increases the over-all cost per kilowatt-hour by the amount which is given directly by the percent-deficiency curve, when the cost per kilowatt-hour of the steam supply itself is a constant unit price. This is not true when the cost of the steam supply is an amount proportional to its capacity plus an increment proportional to its output; this, the general case, will be discussed below.

This curve, therefore, determines one of the principal factors that fixes the economical size of the auxiliary plant. As an illustration, assume that in the given market the "continuous"

supply can be sold for 2 mills per kilowatt-hour more than the variable supply will bring. Allowing a certain margin, an additional cost of the total supply of 1.5 mills per kilowatt-hour may be justified, thus leaving a margin of 0.5 mills for profit. The

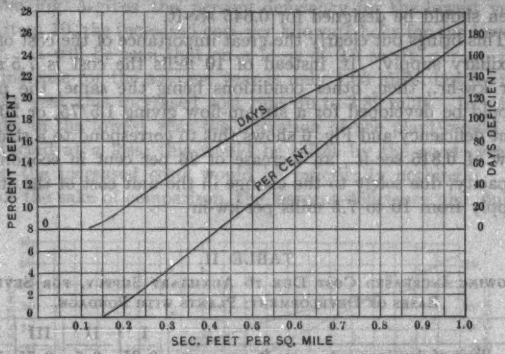

FIG. 6—AVERAGE PERCENT-DEFICIENCY AND AVERAGE DURATION CURVES FOR THE SUSQUEHANNA RIVER AT MCCALL FERRY FOR THE TWENTY YEAR PERIOD 1891-1910.

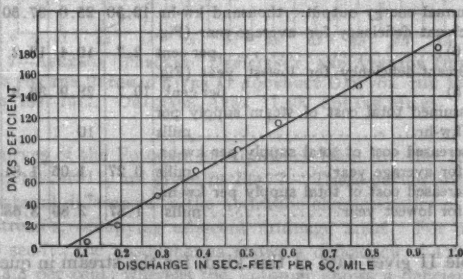

FIG. 6A—AVERAGE DURATION CURVE: STRAIGHT LINE ASSUMED FOR APPROXIMATE PURPOSES—EQUATION OF CURVE—

$$Q = 0.08 + \frac{D}{220}$$

development should then be fixed at such a point that the burden of the auxiliary supply when spread over the total output will amount to not more than 1.5 mills per kilowatt-hour. Assume also that it is known, from the conditions of operation, that the

total annual cost of the auxiliary supply will be 10 mills per kilowatt-hour; then the hydraulic plant should be developed to the point where the deficiency is 1.5/10 or 15 per cent of the total output. Fig. 6 shows at once that this deficiency, for this stream, is reached at a stream-flow of 0.645 sec-ft.; the plant then should be designed for 0.645 sec-ft.

This brings out clearly the great importance of the cost of the auxiliary supply. If, instead of 10 mills the cost is 7.5 mills per kw-hr., then, other conditions being the same, the plant should be developed for a stream-flow giving 1.5/75, or 20 per cent deficiency and Fig. 6 shows this to correspond to a stream-flow of 0.815 sec-ft., an increase of 26 per cent in economical capacity, due solely to the change in the unit cost of the steam supply from 10 to 7.5 mills per kw-hr.

TABLE II.

SHOWING INCREASED COST DUE TO AUXILIARY SUPPLY, FOR SEVERAL BASES OF DEVELOPMENT: PLANTS WITH PONDAGE.

	I	II	III	IV
1. Basis of development....sec-ft. per sq.mi.	0.25	0.5	0.75	1.0
2. Assumed head.....ft.		100		
3. Efficiency to substation.....per cent		67		
4. Power at substation.....kw.	1.43	2.85	4.27	5.7
5. Annual energy output...thousand kw-hr.	12.50	25.0	37.50	50.0
6. Percent deficiency for average year (Fig. 6).....per cent	2.7	10.4	18.2	25.4
7. Percent-deficiency for lowest year (Fig. 5).....per cent.	10.7	28.9	36.8	43.0
8. Assumed total cost of steam supply per kw-hr..... mills		10		
9. Increased cost of total supply per kw-hr. for average year.....mills	0.27	1.05	1.81	2.54
10. Increased cost of total supply per kw-hr. for lowest year.....mills	1.87	2.89	3.68	4.30

Table II gives data of this kind, for the stream in question, on four assumptions as bases of a development, viz., 0.25, 0.5 0.75 and 1.0 sec-ft. per square mile. In order to make the case concrete a head of 100 ft. is assumed. The other data of the table follow directly from these assumptions and from the curves already given. Item 6 gives the percent-deficiency in the average year, and from what has been said above, it follows at once that the increased cost per kilowatt-hour of the total supply is directly proportional to these figures, when the unit cost of

this supply is constant; for a 10 mill cost the increment costs are given by item 9, for the average year. In the long run, the costs for the average should be controlling, but it is well to know what would be the operating results in the lowest year. Item 7 from Fig. 5 gives the percent-deficiency for the lowest year and item 10, the increased cost per kilowatt-hour for the lowest year. It will be seen that on a basis of 0.5 sec-ft. per sq. mi. the increase for the average year is only 1.05 mills, but for the lowest year this increased cost runs up to 2.89 mills. In other words, in the lowest year the operation of the plant would be conducted at a loss; this would be offset by the good years, when the increased costs would be practically nothing.

For the sake of comparison, the percent-deficiency and dura-

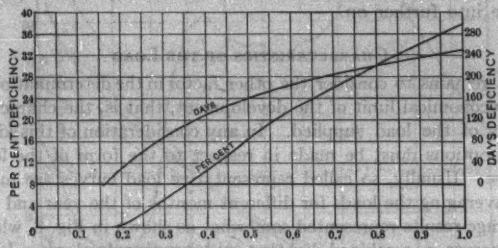

FIG. 7—AVERAGE PERCENT DEFICIENCY AND AVERAGE DURATION CURVES FOR THE POTOMAC RIVER AT AQUEDUCT DAM FOR THE 15-YEAR PERIOD 1897-1911. DRAINAGE AREA 11,400 SQUARE MILES.

tion curves of the Potomac at Aqueduct Dam for the 15-year period, 1897-1911, are given in Fig. 7. These curves bring out the material differences in the hydraulic characteristics of these two streams, occupying adjacent drainage areas. For a flow of 0.6 sec-ft., the Susquehanna shows a deficiency of 119 days and 13.5 per cent; whereas the Potomac shows a deficiency of 184 days and 21.7 per cent. If then, plants were developed at these streams for a flow of 0.6 sec-ft., the cost of the steam reserve for the Potomac would be materially greater than that for the Susquehanna, as 8.2 per cent more of the total energy would have to be supplied by steam. If the total cost of the steam supply were 10 mills, then for the Potomac the addition to the hydraulic cost would be 2.17 mills per kw-hr.; whereas for the Susquehanna the addition would be only 1.35 mills.

Another way to consider the relative value of the two streams is to determine the development for which the percent-deficiency will be the same. For the Potomac the deficiency of 13.5 per cent corresponds to a stream flow of approximately 0.46 sec-ft. That is, based on equal energy deficiency and consequently, the same size and output of steam plant, when operating on the same load curve, the economical development for the Susquehanna would be 30 per cent greater than for the Potomac. The difference is really greater, since a hydraulic development for greater capacity will generally mean a reduced unit cost. The plans under consideration for the Potomac at Great Falls are for a development at 0.6 sec-ft.

For plants without pondage it is necessary to consider the shape of the load curve in determining the deficiency. This is gone into further on.

Characteristics of the Load

It remains to consider the other factor in the determination of the economical limit of the development, that is, the characteristics of the load supplied. In any consideration of this kind, assumptions must be made in respect to the form of the load curve. Usually, so called representative load curves are made by averaging the loads for different months of the year and the average results represented somewhat as shown in Fig. 8, which represents a combined lighting and traction load of a large city. This curve is plotted with the maximum power as 100 instead of in kilowatts: that is, the ordinates are reduced to a percentage basis. This is done to give greater generality, just as the hydraulic curves were plotted in sec-ft. per sq. mi.

From the usual load-curve shown, there is derived a curve that I call the "percent-load" curve, for want of a better name. This is shown at $Y\ R\ P\ L\ X$, Fig. 8. The ordinates of this curve give the relative power, with maximum power at 100, and the abscissas give the "peak-energy" expressed in terms of the total energy as 100. Referring to Fig. 8, the abscissa $O\ K$ of the point P gives the percentage of the total energy that is included above the power line $N\ Q\ P\ U$. The co-ordinates are then "peak-energy" and "base-power." "Base-energy" and "base-power" might have been used, but the choice made simplifies the use of the curve. "Base-energy" is given by the abscissa measured to the left from X, that is, "base-power" is $K\ P$ and "base-energy" $K\ X$: "peak-power," $N\ Y$, and "peak-energy," $N\ P$.

This curve is made up of two parts, a straight line from X up to the point L of minimum power, $M\,S\,L$, and a curve tangent to this straight line $X\,L$ at the point L. This part $X\,L$ is straight, because energy and power are directly proportional up to the point of minimum power.

This "percent-load" curve possesses several interesting properties:

1. A tangent at the point L, that is, the line $X\,L$ continued,

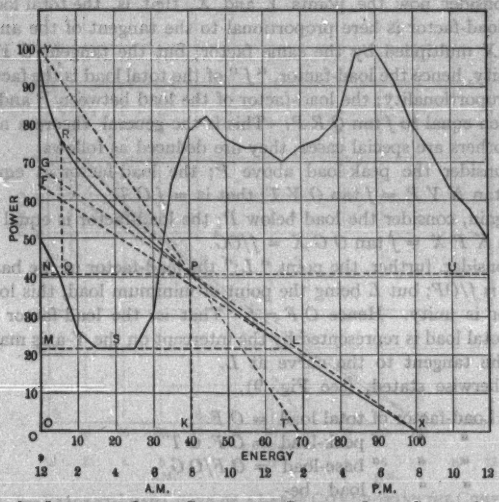

FIG. 8—ORDINARY LOAD CURVE AND PERCENT-LOAD CURVE CORRESPONDING TO IT.

intercepts the Y-axis at the point F, and $O\,F$ is the load-factor of the total load.

2. A line drawn from Y through any point P will intersect the X-axis at point T, and the load-factor of the peak-load above P is equal to the load-factor of the total load $O\,F$ multiplied by $O\,T$ or $O\,F.\,O\,T$.

3. A line drawn from X through the point P intersects the Y-axis at the point G, and the load-factor of the base-load is $O\,F/O\,G$.

These theorems can be proved in a simple manner. Consider any two points P and R on the "percent-load" curve; the energy between them is proportional to the difference between the abscissas of the two points, that is to $P\,Q$: the power is proportional to the differences between the ordinates, that is to $R\,Q$: the load-factor of the load between these two points is then proportional to $P\,Q/R\,Q$, that is to the tangent of the angle $Q\,R\,P$. The load-factor is then equal to the tangent of this angle multiplied by a factor of proportionality.

Consider now the points Y and X, that is, the total load: the load-factor is here proportional to the tangent of the angle $O\,Y\,X$ multiplied by the same factor; but the tangent $O\,Y\,X$ is unity, hence the load-factor, "f" of the total load is the factor of proportionality; the load-factor of the load between P and R is then equal to $f \tan Q\,R\,P$. This is the general theorem and the others are special cases; they are deduced as follows:

Consider the peak-load above P; the load-factor is equal to $f \tan N\,Y\,P = f \tan O\,Y\,T$; that is $= f\,O\,T$.

Again, consider the load below P; the load-factor is equal to $f \tan K\,P\,X = f \tan O\,G\,X = f/OG$.

Consider, further, the point "L;" the load-factor of the base-load is f/OF; but L being the point of minimum load, this load factor is unity. Hence $O\,F = f$. That is, the load-factor of the total load is represented by the intercept on the Y-axis made by the tangent to the curve at L.

Otherwise stated, (see Fig. 9),

1. Load-factor of total load $= O\,F$
2. " " " peak-load $= O\,F.\,O\,T$
3. " " " base-load $= O\,F/O\,G$
4. " " " load between P and R $= O\,F \tan Q\,R\,P$

This curve enables one to determine at once the capacity of the steam plant required to meet any assumed conditions of the hydraulic development, for plants with pondage. In fact, the curve itself gives the capacity of the steam plant for any ratio of minimum to rated stream-flow. This can be seen by reference to Fig. 9, on which is reproduced the percent load curve of Fig. 8, for the sake of clearness. The abscissa of any point of the curve is the ratio of peak-energy to total energy. It therefore represents, for plants with pondage, the ratio of minimum stream-flow to rated stream-flow, since the ratio

of stream-flow is the ratio of hydraulic energy available for use to total energy required by the load, and the hydraulic energy is used for the peak-load. The ordinate of the point represents base-power, which is the portion of the load not supplied by the hydraulic plant and which must be supplied by the steam plant. In other words, this curve represents, for plants with pondage, the relation between the ratio of minimum flow to rated flow and the capacity of steam plant required, in per cent of maxi-

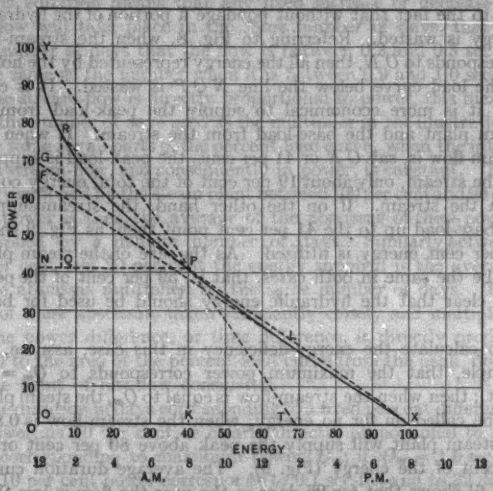

FIG. 9—PERCENT-LOAD CURVE OF A LARGE CITY SHOWING THE COMBINED POWER, LIGHTING AND TRACTION LOADS.
ORDINATES: BASE-POWER
ABSCISSAS: PEAK-ENERGY

mum power. For instance for a minimum flow of 20 per cent of the rated flow, the capacity of the steam plant required is 58 per cent of the maximum power; for a ratio of minimum flow to rated flow of 50 per cent, the capacity of the steam plant required is 33 per cent. This load-curve then gives at once the capacity of the steam plant required for the entire range of operating conditions.

For plants without pondage, the greatest proportion of the possible energy of the stream-flow, under low water conditions,

can be made available by supplying the base-load from the stream up to its power capacity. If the flow is 20 per cent of the rated flow, then the steam plant will have a capacity of 80 per cent of the maximum. It should be noted also that the rated-stream flow, for plants without pondage, is equal to the rated flow for plants with pondage multiplied by $1/f$, assuming the same load curve, *i. e.*, the maximum in one case, the average in the other.

The determination of the energy deficiency for plants without pondage is less simple than in the case of pondage. This is due to the fact that without pondage a portion of the hydraulic energy is wasted. Referring to Fig. 8, when the stream-flow corresponds to $O\ N$, then all the energy represented by the hollow of the load curve below the line $N\ Q\ P$ is wasted. It is clear that it is more economical to supply the peak-load from the steam plant and the base-load from the stream. If when the stream-flow is, say $O\ N$ or 41 per cent, the peak-load is supplied by the stream, only about 19 per cent of the total energy comes from the stream. If on the other hand, the stream supplies the base-load up to the 41 per cent point then, as Fig. 9 shows 60 per cent energy is utilized. As the size of the steam plant will be the same in both cases, that is, 59 per cent of the peak, it is clear that the hydraulic energy should be used for base-load.

To calculate the energy-deficiency in this case, assume, for example, that the maximum power corresponds to $Q_m = 0.5$ sec-ft.; then when the stream-flow is equal to Q_m, the steam plant will be called on for no energy; when the stream-flow is $0.8Q_m$ the steam plant will supply the peak above 80 per cent or 4.0 per cent of the energy (Fig. 9). The average duration curve, (Fig. 6) shows that for 96 days of the year the flow is less than 0.5 sec-ft. and for 73 days less than 0.4 sec-ft.; that is, for 23 days the flow will be between that required for maximum power and 80 per cent power. The steam plant will be supplying, during these 23 days, energy varying from nothing to 4 per cent, an average of 2 per cent; the total output of the steam plant for this period will then be proportional to 23×2 per cent. This procedure, carried out step by step and the results summed up and averaged, will give the energy to be furnished by the steam plant during the low-water period, for the load curve used.

But this method is somewhat tedious and the data is not sufficiently accurate to justify any refinement; hence an approximation is developed, based on the assumption that the average

duration curve may be represented sufficiently well for this purpose by a straight line.

That this average duration curve is nearly a straight line is shown in Fig. 6A where the actual points, and the assumed straight line are shown; the equation of the line is

$$Q = Q_0 + D/d \tag{3}$$

$$Q = 0.08 + D/220 \tag{3a}$$

This equation means that any fixed increase or decrease in the flow will take place in the same number of days, that is, the number of days that the flow is between 0.2 and 0.3 sec-ft. is the same as the number when it is between 0.9 and 1.0 sec-ft. As the stream-flow is directly proportional to power, this means that the number of days used as the multiplier in the illustration, is the same for all parts of the percent-load curve, when the interval in stream-flow, and consequently in power, is constant. The energy supplied by the steam plant between 100 per cent and 90 per cent power is then the average of the abscissas of these points multiplied by a definite number of days. Similarly between 30 per cent and 20 per cent the energy supplied is the average of the abscissas multiplied by the same number of days. The sum of these abscissas, taken sufficiently closely and multiplied by the power difference, or time difference, is directly proportional to the area of the percent-load curve from the peak down to the point of low-flow considered.

The duration in days corresponding to a fixed per cent difference in power, as 10 per cent, is clearly directly proportional to the flow corresponding to maximum power, Q_m; if $Q_m = 1.0$ sec-ft. then 10 per cent power corresponds to 0.1 sec-ft., and to 22 days from eq. (3a). But if Q_m is 0.5 sec-ft., then 10 per cent power corresponds to 0.05 sec-ft., and to 11 days. The per cent energy deficiency is then proportional to the flow for maximum power Q_m.

It can easily be shown that the energy deficiency in per cent,

$$p_e = 100\, Q_m \times d/365 \times \left(\frac{\text{Area above } P_0}{10^4}\right) \tag{4}$$

As 10^4 represents the area of the square enclosing the curve $Y\,R\,P\,L\,X$, the ratio of the areas is shown graphically; (d) is the number of days to increase the flow by one sec-ft., Q_m the flow corresponding to maximum power.

The practical way to calculate this deficiency is to take the abscissas of the average power interval, add them up, multiply by the corresponding number of days and divide by 365, thus getting the average per cent deficiency.

For example:

$Q_m = 1.0$; 10 per cent power intervals; days corresponding to 10 per cent = 22

$Q_0 = 0.2$ sec-ft.

Calculate the average peak-energy for each step of 10 per cent of the power down to the minimum power, 20 per cent, as follows:

Average peak-energy between power values of	Per cent
100–90	0.5
90–80	2.5
80–70	6.8
70–60	14.0
60–50	23.7
50–40	35.0
40–30	47.5
30–20	61.5
Sum	191.3

Hence average percent-deficiency $= 191.3 \times 22/365$
$= 11.5$ per cent.

If Q_m had been 0.5, then the number of days corresponding to the 10 per cent power interval would have been 11, and the per cent-deficiency would have been $11.5/2 = 5.75$ per cent.

It is simpler and sufficiently accurate to take the abscissa of the average power ordinate for each step, instead of the average of the abscissas of the two limiting power values.

Typical Percent-Load Curves

This completes the consideration of necessary capacity of the steam plant and its output, for hydraulic plants both with and without pondage, and for any stream flow corresponding to the rated capacity.

The method then depends upon the use of three curves; the "percent-deficiency" and the "duration" curve, characterizing the hydraulic features of the development and the "percent load" curve, characterizing the power load. It remains now to show how the results so far arrived at, can be applied to determine the increased cost of the auxiliary supply and consequently the economical point of the development, considered in the light of the actual conditions of the power market.

Before doing this, however, some examples of percent-load curves will be given, in order to bring out the variation of these curves with different conditions.

Fig. 10 gives the percent-load curve of a medium size traction system with some light and power service, in an eastern city; the maximum power of this load was approximately 15,000 kw. The curve is that of a single day, not an averaged curve. Fig. 11 gives the curve for a traction system of a western city, the maximum power being approximately 7000 kw. An examina-

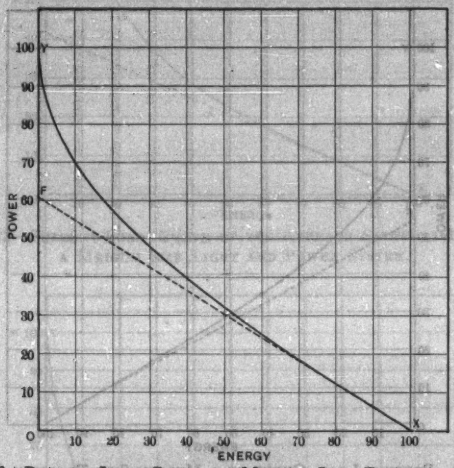

FIG. 10—PERCENT-LOAD CURVE OF MEDIUM SIZE TRACTION SYSTEM IN AN EASTERN CITY.

tion of these two curves shows that of Fig. 11 to be a more peaked curve. For instance Fig. 11 contains less than six per cent of the energy in the 30 per cent peak, whereas Fig. 10 shows 10 per cent. Fig. 11 shows 21 per cent of the energy for the 50 per cent peak, whereas Fig. 10 shows 28 per cent. The total load-factors do not differ greatly, being 54 per cent in the one case and 61 per cent in the other.

Figs. 12 and 13 show the percent-load curves for the same system, Fig. 12 being the averaged curve of twelve Saturday curves, one for each month of the year, and Fig. 13 the averaged

curve of the twelve succeeding Mondays. These show well the difference in the characteristics of the load of the same system for different days. This difference would be reflected in the capacity of the steam plant required for reserve. With a stream-flow of 20 per cent of the rated flow, (with pondage), the load of Fig. 12 would require a steam plant of 50 per cent capacity, whereas, the load of Fig. 13 would require only 44 per cent. For a 10 per cent ratio, Fig. 12 requires 70 per cent and Fig. 13, 59 per cent.

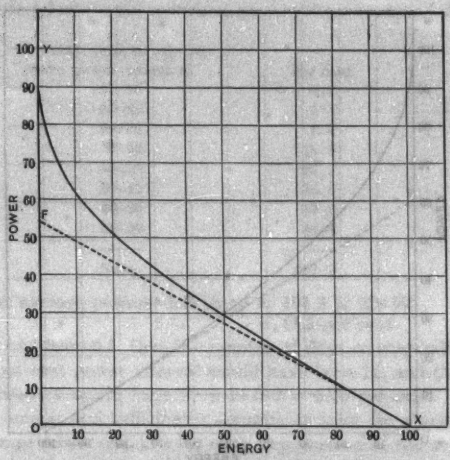

FIG. 11—PERCENT-LOAD CURVE OF A MEDIUM SIZE TRACTION SYSTEM IN A WESTERN CITY.

Fig. 14, is to show the difference in capacity of steam plant required for loads having the same total load-factor, but differing in shape. The four load curves shown, all have a total load-factor of 40 per cent; but with a ratio of low flow to the rated flow of 25 per cent, as indicated by $O\ T$, the steam plant capacity required will be 33, 42.5, 54 and 59 per cent of the maximum respectively. The percent-load curve therefore, brings out clearly the fact that the total load-factor is not the determining factor in fixing the capacity of the auxiliary steam plant.

Fig. 15 gives the "annual percent-load" curve of the light-

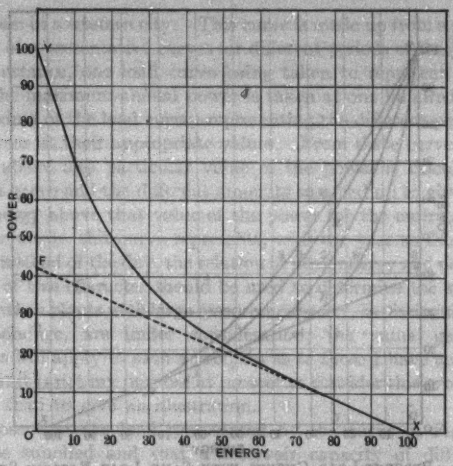

FIG. 12—PERCENT-LOAD CURVE OF THE AVERAGE SATURDAY LOAD OF A MEDIUM SIZE LIGHT AND POWER SYSTEM.

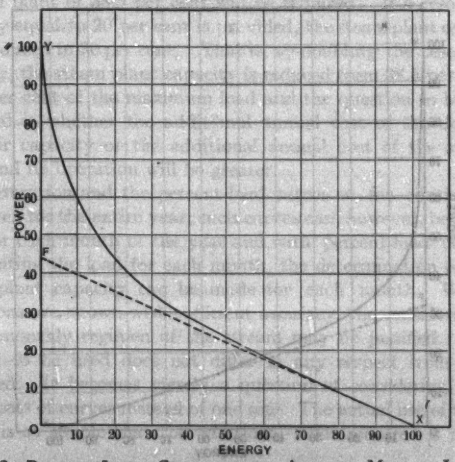

FIG. 13—PERCENT-LOAD CURVE OF THE AVERAGE MONDAY LOAD OF THE SAME SYSTEM AS FIG. 12.

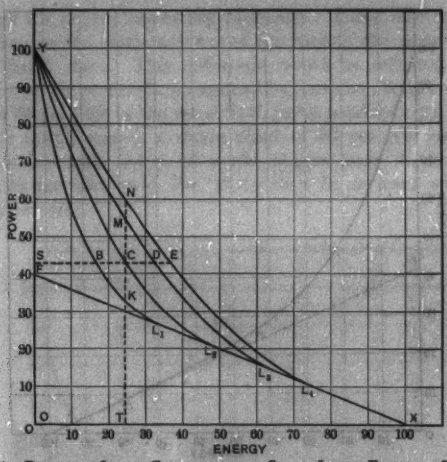

FIG. 14—PERCENT-LOAD CURVES WITH SAME LOAD FACTOR, SHOWING DIFFERENT AUXILIARY POWER REQUIREMENTS.

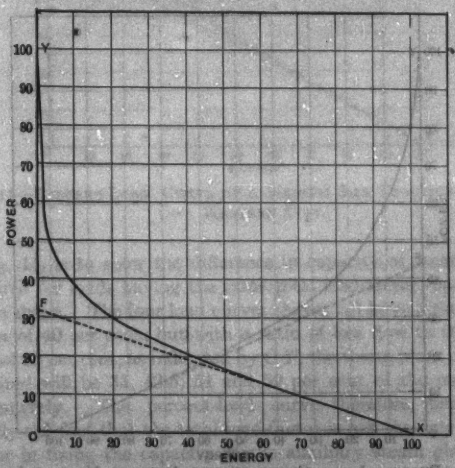

FIG. 15—ANNUAL PERCENT-LOAD CURVE OF A LIGHT AND POWER SYSTEM OF A WESTERN CITY.

ing system in a western city. This curve is made up from a large number of representative curves for different periods of the year; as for instance, one load curve being taken to represent each week; the maximum annual power is taken at one hundred and the maxima of the load curves representing the different periods of the year at their appropriate values. From these curves the energy above any particular value of the power is calculated for each curve and the different amounts summed up to give the total energy above that value of the power for the entire year. In other words, this curve represents, with the year as the unit of time instead of the day, the relation of peak-energy and power. Curves of this character should be used to determine the steam reserve when plants with large reservoir capacity, as distinguished from pondage, are under consideration; the same general methods will apply to such a problem as to those I have considered, but it is not my purpose at present to consider this problem further than to give an illustration.

Suppose that the load represented by the curve of Fig. 15 is to be supplied and that a reservoir capacity of different amounts can be obtained at increasing expenditures. If a reservoir capacity equal to 10 per cent of the energy is available a steam plant of 38.5 per cent will be required. If a reservoir capacity equal to 20 per cent is provided, the steam plant capacity is reduced to 30 per cent. That is, by doubling the reservoir capacity, the steam plant capacity is reduced from 38.5 per cent to 30 per cent of the maximum load and the question to be determined is whether the additional annual cost of the double reservoir capacity or the additional annual cost of the steam plant and its operation will be greater.

The duration and the percent-load curves so far considered have been for the entire year; such curves can, however, be compiled for each month of the year and with percent-load curves representing the load for each month, the determination of the steam plant capacity can be made for each month. Where conditions are known with sufficient accuracy, the consideration of the monthly regimen of the stream may be justified. The method to be used does not differ in any respect from that discussed. It becomes merely a question of considering, say, twelve sets of curves instead of one set. The actual use of these curves is so simple that the additional labor required is negligible.

The minimum flow of the stream to be used may be the ab-

solute minimum, the minimum of the average year, the average minimum, or some other value of low discharge of the stream. The selection of the particular value to be used depends upon the degree of insurance of the continuity of the supply that is justified by the conditions. The added cost of the insurance of the supply should be equated to the losses, direct and indirect, sustained by failure of the supply. If it is planned to secure absolute continuity, in as far as stream-flow is concerned, it will be necessary to use the absolute minimum of the stream and to use it in connection with the maximum load that can occur upon any day when the stream-flow may be lowest. This degree of insurance is seldom necessary; usually it will be sufficient to use the stream-flow which can be depended on for, say four years out of five; in other words, to eliminate the extraordinarily low discharge which will occur once in every five to ten years. But on this point, as in all others in connection with the matter, the decision depends upon the experience and judgment of the engineer, and no hard and fast rule can be laid down. One kind of load demands the highest degree of insurance, whereas loads of a different character may be satisfactorily served with a less degree of insurance.

Cost of Hydroelectric Plants

This completes the description of the method of determining the capacity and output of the auxiliary steam plant required for any conditions of load and stream-flow. It is seen to depend on the use of two curves, the percent-deficiency curve and the percent-load curve. For plants with pondage, the ratio of low-flow to rated-flow fixes the capacity of the steam plant, through the use of the percent-load curve, and its energy output is determined by the percent-deficiency curve. For plants without pondage, the capacity of the steam plant is fixed by the ratio of the low-flow to rated-flow and its output is determined by the percent-load curve.

The application of this method depends upon the determination of the cost of an hydroelectric development at any given site over a range of capacities. The cost per kilowatt for the development for low stream flow will obviously be very high, but will decrease as the rated flow of the development increases. In order to use the method, it is necessary to know the annual cost of the hydraulic development per kilowatt of its capacity throughout the range of capacities under consideration, inasmuch as this cost added to the annual cost of the steam plant gives the total annual cost of the combined plant per kilowatt. In

any specific case detailed estimates of the total cost of the hydraulic development for the range of capacities should be used, but in order to discuss the matter generally some assumption must be made covering the cost per kilowatt of a hydraulic development at a given site, for several capacities of equipment.

The cost of any hydroelectric development is made up of certain items that are independent of the capacity of the equipment installed and others proportional to the capacity; in most hydroelectric plants, the fixed costs are materially greater than the variable costs. The relative amounts of these two items vary with the different character of plants, but within a reasonable range of capacity, the assumption that total cost is a constant plus an amount proportional to capacity is sufficiently true to serve in a discussion of this kind. In any concrete case, the accurate method to determine cost for various capacities is to make detailed estimates for the several projects.

TABLE III.

RELATIVE COST OF SOME HYDROELECTRIC PLANTS.

Plant No.	Proportion of Total Cost that is Fixed	Proportion of Total Cost that is Variable
1	70 per cent	30 per cent
2	72 "	28 "
3	40 "	60 "
4	72 "	28 "
5	72 "	38 "
6	58 "	42 "
7	67 "	33 "
8	68 "	32 "
9	77 "	23 "
10	76 "	24 "
11	77 "	23 "
12	68 "	32 "
Average	68 per cent	32 per cent

Table III gives the division between the fixed portion of the cost and the variable portion for twelve different plants, covering high head, medium head and low head plants, some with flumes, canals, or pipe lines, and others with heavy concrete dams and no water-ways. The data of this table are taken from a number of sources; several are my estimates, some are from the reports of other engineers and others are from published

statistics. In some cases, detailed estimates have been prepared by the engineer for several different capacities; in others, the items of cost as given for the normal development are divided into an assumed fixed part and a variable part; the variable part is then taken to be proportional to the capacity.

The data of this table may be somewhat surprising. One would probably think that the cost of an hydraulic plant for high head with flume lines, canals, penstocks, and without storage, would be in greater part proportional to capacity, than would a plant with a large concrete dam and no waterways. But the preliminary costs, riparian rights, removal of railroads and roads, real estate, right-of-way for transmission line, charters, legal expenses, banker's expenses, and various items that are not directly dependent upon the capacity, together with that part of the cost of the equipment which is in itself not directly proportional to capacity, make up a large part of the total cost, even in such cases.

For want of a better generalization covering the cost of an hydraulic development, it will be assumed that the total cost is composed of a fixed portion plus a portion proportional to the capacity; it being always kept in mind that this is done simply to illustrate the method described and not as an attempt to formulate a general rule. The results from this assumption check well, in certain cases, with detailed estimates based on actual figures of cost of developments at the same site, for various capacities.

TABLE IV.

VALUES OF $k_r = (a/r + b)$

r	$a = 0.75$ $b = 0.25$	$a = 0.67$ $b = 0.33$	$a = 0.60$ $b = 0.40$	$a = 0.50$ $b = 0.50$
0.5	1.75	1.67	1.60	1.50
1.0	1.00	1.00	1.00	1.00
1.5	0.75	0.78	0.80	0.83
2.0	0.63	0.67	0.70	0.75

Let, then,

a = the part of the cost of the plant, in per cent, that does not vary with the capacity,

b = the part that is proportional to capacity,

r = the ratio of the capacities, taking some intermediate capacity of plant as unity, in order that the range in capacity may be kept as narrow as may be.

Then the ratio of total cost of plants for various capacities is represented by $(a + r\,b)$
and the ratio of the cost per kilowatt of capacity is

$$k_r = (a/r + b) \tag{4}$$

For plants both with and without pondage, the ratio of capacity is the ratio of rated stream-flow, since the same load curve is assumed for the several capacities, that is the same power market.

If then, Q_1 is the stream-flow for the basic capacity, *i.e.* for $r = 1$ and Q_r is for any other capacity,

then $$r = Q_r/Q_1. \tag{5}$$

The annual charges on a hydroelectric plant are practically independent of the energy output; this is strictly true for the fixed charges, such as interest, depreciation, insurance, taxes, etc., and is approximately true for the cost of management. Inasmuch as the investment cost per kilowatt of the combined plants will vary over a wide range, profit must be included with fixed charges in order to determine the economical development. It is assumed that there is market at a known price and the question is to determine at what price energy can be sold from the various developments; therefore selling price and not cost must be determined. In what follows, I take for the fixed charges for the hydroelectric and steam plants the following:

TABLE V.

	Hydroelectric	Steam
Interest and profit	10 per cent	10 per cent
Depreciation and obsolescence	2 "	7 "
Insurance and taxes	1 "	2 "
Management	1 "	1 "
Total	14 per cent	20 per cent

Depreciation in a hydroelectric plant affects only a small portion of the total development, the equipment; whereas in a steam plant practically the entire plant is subject to depreciation. Similarly, obsolescence due to changes in the art is practically non-existent in an hydroelectric plant, since the plant can-

not be changed in any reasonable way in order to obtain a higher efficiency, whereas with a steam plant it is well known there is a constant change due to the improvements in the economy of machines. The fundamental reasons for the greater permanence for the hydraulic plant is the fact that the efficiency of the conversion of energy in this case is high, say 80 per cent, whereas with a steam plant it will not exceed 12 per cent. The margin for possible improvement is then very small in the one case and very great in the other. Further, the hydraulic plant, once built, cannot well be radically changed, even though the efficiency of the waterwheels should be made greater, and if such changes could be made they would not be economical, owing to the great cost of changes in the entire construction of the plant.

Insurance and taxes are less for the hydraulic plant on account of the different character of the property, and also due to the fact that the plant itself is usually in a country district where the tax rate is lower than in a city.

The cost of operation and maintenance of a hydroelectric plant is practically independent of its output, and only in part proportional to its capacity. It is, however, relatively to fixed charges and profit, so small that no error of moment will be made by assuming it to be proportional to capacity.

The total annual cost will then be as follows:

Let

i_h = the sum of all charges and profit, in per cent

C_h = the capital cost of the plant per kw. of maximum capacity at basic rating, *i.e.* for $r = 1$.

O_h = the total operating and maintenance cost per kw. for basic capacity,

$k_r = a/r + b$ = the ratio of cost per kw. to basic cost.

Then will

$$\text{Total annual cost per kw.} = A_h = i_h k_r C_h + O_h k_r$$
$$= k_r (i_h C_h + O_h) \qquad (6)$$

Annual Cost of Steam Plant

To this annual cost must be added the total cost of the steam plant, determined for the conditions of operation fixed by the "percent-deficiency" and the "percent-load" curve. This is done as follows:

Let

c = the annual fixed charges in dollars on the steam plant per kw. of its own capacity, including interest, profit, depreciation, taxes, insurance and pay roll for the term during which the plant will be in commission, usually for 7 to 10 months, and also including a certain portion of the fuel, that part required to bank fires, or to keep the plant ready for quick operation.

m = the increment cost of energy production in mills per kw-hr. This will include only fuel and minor supplies.

p_e = the percent energy deficiency for the average year under the assumed conditions.

p_c = the relative capacity of the steam plant required to meet the assumed conditions.

h = the number of hours equivalent to the load-factor, from the percent-load curve, divided by 1000, *i.e.* $= f \times 8760/1000$, where f is the load-factor.

Then the annual cost of the steam plant per kw. of total load is

$$A_s = c\,p_c + h\,m\,p_e \tag{7}$$

A_s is the increased annual cost per kw. of total load, which is imposed by the steam plant.

From this, the increased cost in mills per kw-hr. of the total output due to the addition of the auxiliary steam plant is

$$A_s/h = c\,p_c/h + m\,p_e \tag{8}$$

The selling price is then given by

$$S = A_h + A_s \tag{9}$$

Examples of Use of Method

The application of this method to certain assumed conditions is given in the tables following. Example I gives the total annual cost for the Susquehanna for developments rated at 0.25, 0.5, 0.75 and 1.0 sec-ft. per square mile for a plant with pondage and for a load having a high load-factor of 64 per cent. The results are first calculated for an investment cost of $100 per kilowatt for the hydraulic plant, when developed for a rated flow of 0.5 sec-ft., and for an annual cost of $10 per kilowatt, covering the fixed charges of the steam plant, corresponding to an investment cost of $50 per kilowatt, if 20 per cent be taken for fixed charges. An addition is then made to the figures thus obtained to cover an investment cost of the hydraulic plant of

$150 per kilowatt and also to cover fixed charges at $15 per kilowatt for the steam plant. The annual cost for four different conditions is then given in the table; that is for hydraulic cost of $100 and annual steam cost of $10; hydraulic cost of $100 and annual steam cost of $15; hydraulic cost of $150 and annual steam cost of $10; hydraulic cost of $150 and annual steam cost of $15. Throughout, the increment operating cost of the steam plant is taken at 3 mills per kw-hr.

EXAMPLE I: Plant with pondage:

Load of Fig. 9, load-factor 64 per cent, $h = 5500/1000$,

Assume

$k_r = 0.67/r + 0.33$: $Q_r = 0.5$, for $r = 1$; minimum flow $Q_0 = 0.1$

$C_h = \$100$, $O_h = \$1$, $i_h = 14$ per cent.

Hence

$(i_h C_h + O_h) = \$15 = A_h/k_r$; $A_h = \$15\, k_r$;

Also $c = \$10$, $m = 3$ mills; $m\, h\, p_s = \$16.50\, p_s$.

TABLE VI.

1.	Rated stream-flow, Q_r, sec-ft.	0.25	0.50	0.75	1.00
2.	Ratio of capacity, $Q_c/0.5$	0.50	1.0	1.50	2.0
3.	Percent-deficiency, p_s, (Fig. 6)	2.7	10.4	18.1	25.4
4.	Minimum/rated-flow, $0.1/Q_r$	0.4	0.2	0.13	0.10
5.	Steam plant capacity, p_c, (Fig. 9)	0.41	0.58	0.65	0.69
6.	Hydraulic cost ratio, k_r (Table V)	1.67	1.00	0.78	0.67
7.	$\$10 \times p_c$ (line 5)	$4.10	$5.80	$6.50	$6.90
8.	$\$16.50 \times p_s$ (line 3)	0.45	1.72	2.95	4.20
9.	$A_s = (7) + (8)$ = Steam cost	4.55	7.52	9.45	11.10
10.	$A_h = \$15\, k_r$ = Hydraulic cost	25.00	15.00	11.70	10.00
11.	$S = A_s + A_h$ = Total cost	$29.55	$22.52	$21.15	$21.10
The increment to be added to line (11) for					
12.	$C_h = \$150$ is	$11.70	$7.00	$5.48	$4.70
13.	$c = \$15$ is	2.05	2.90	3.25	3.45
And therefore for					
14.	$C_h = \$100$ $c = \$15$, S is	31.60	25.42	24.40	24.55
15.	$C_h = \$150$ $c = \$10$, S is	41.25	29.52	26.63	25.80
16.	$C_h = \$150$ $c = \$15$, S is	43.30	32.42	29.88	26.25

Example II embodies the same data as Example I, except that a load having a medium load-factor of 42.5 per cent is taken. Example III is the same as Example I except that a load having a low load-factor of 32 per cent is taken.

EXAMPLE II: Same as Example I, except that load-curve of Fig. 12 is used. Load-factor 42.5 per cent: $h = 3700/1000$

$m\, h\, p_s = \$11.40\, p_s$.

TABLE VII.

1. Rated stream flow, Q_r, sec-ft.	0.25	0.50	0.75	1.00
2. Ratio of capacity, $Q_r/0.5$	0.5	1.0	1.50	2.0
3. Per cent-deficiency, p_e, (Fig. 6)	2.7	10.4	18.1	25.4
4. Minimum/rated-flow, $0.1/Q_r$	0.4	0.2	0.13	0.10
5. Steam plant capacity, p_c (Fig. 12)	0.29	0.51	0.63	0.71
6. Hydraulic cost ratio, k_r (Table V)	1.67	1.00	0.78	0.67
7. $\$10 \times p_c$ (line 5)	$2.90	$5.10	$6.30	7.10
8. $\$11.40 \times p_e$ (line 3)	0.30	1.15	2.06	2.82
9. $A_s = (7) + (8)$ = Steam cost	3.20	6.25	8.36	9.92
10. $A_h = \$15\ k_r$ = Hydraulic cost	25.00	15.00	11.70	10.00
11. $S = A_s + A_h$ = Total cost	$28.20	$21.25	$20.06	$19.92
The increment to be added to line (11) for				
12. $C_h = \$150$ is	$11.70	$7.00	$5.48	$4.70
13. $c = \$15$ is	1.45	2.55	3.15	3.55
And therefore for				
14. $C_h = \$100$; $c = \$15$, S is	29.65	23.80	23.21	23.47
15. $C_h = 150$; $c = 10$, S is	39.90	28.25	25.54	24.62
16. $C_h = 150$; $c = 15$, S is	41.35	30.80	28.69	28.17

EXAMPLE III: Same as Example I, except that load-curve of Fig. 15 is used. Load-factor, 32 per cent, $k = 2800/1000$.

$$m\ k\ p_c = \$8.40\ p_e.$$

TABLE VIII.

1. Rated stream flow, Q_r, sec-ft.	0.25	0.50	0.75	1.00
2. Ratio of capacity, $Q_r/0.5$	0.5	1.00	1.50	2.0
3. Per cent-deficiency, p_e (Fig. 6)	2.7	10.4	18.1	25.4
4. Minimum/rated-flow, $0.1/Q_r$	0.4	0.2	0.13	1.10
5. Steam plant capacity, p_c (Fig. 15)	0.21	0.30	0.35	0.39
6. Hydraulic cost ratio, k_r (Table V)	1.67	1.00	0.78	0.67
7. $\$10\ p_c$ (line 5)	$2.10	$3.00	$3.50	$3.90
8. $\$8.40\ p_e$ (line 3)	0.22	0.87	1.52	2.23
9. $A_s = (7) + (8)$ = Steam cost	2.32	3.87	5.02	6.13
10. $A_h = \$15\ k_r$ = Hydraulic cost	25.00	15.00	11.70	10.00
11. $S = A_s + A_h$ = Total cost	$27.32	$17.87	$16.72	$16.13
The increment to be added to line (11) for				
12. $C_h = \$150$	$11.70	$7.00	$5.48	$4.70
13. $c = \$15$	1.05	1.50	1.75	1.95
And therefore for				
14. $C_h = \$100$; $c = \$15$, S is	$28.37	20.37	18.47	18.08
15. $C_h = 150$; $c = 10$, S is	39.02	25.87	22.20	20.78
16. $C_h = 150$; $c = 15$, S is	40.07	27.37	23.95	22.83

The results from these three cases are summarized in Table IX, which gives the total annual cost per year per kilowatt of combined hydraulic and steam plants, for the four conditions of investment and operating costs stated above. To this is

added a column giving the annual cost of an "all-steam" supply under the same conditions of load. The cost of the steam supply imposes an upper limit to the permissible cost of the combined hydraulic and steam plants, as it is obvious that it would be bad business to develop the combined plant unless a material saving in the total annual cost is thereby obtained.

TABLE IX.

TOTAL PRICE PER KILOWATT-YEAR—FROM TABLES VI, VII AND VIII—AND PRICE FOR AN "ALL-STEAM" SUPPLY.

Q_r = ...	0.25	0.5	0.75	1.00	All Steam
I For C_h = $100: c = $10					
1 Load-factor 64 per cent..	$29.55	$22.52	$21.15	$21.10	$26.50
2 Load-factor 42.5 per cent	28.20	21.15	20.06	19.92	21.10
3 Load-factor 32 per cent	27.32	18.87	16.72	16.13	18.40
II For C_h = $100: c = $15					
1 Load-factor 64 per cent	31.60	25.42	24.40	24.55	31.50
2 Load-factor 42.5 per cent	29.65	23.80	23.21	23.47	26.10
3 Load-factor 32.0 per cent	28.37	20.37	18.47	18.08	23.40
III For C_h = $150: c = $10					
1 Load-factor 64.0 per cent	41.25	29.52	26.63	25.80	26.50
2 Load-factor 42.5 per cent	39.90	28.25	25.54	24.62	21.10
3 Load-factor 32.0 per cent	39.02	25.87	22.20	20.78	18.40
IV For C_h = $150: c = $15					
1 Load-factor 64.0 per cent	43.30	32.42	29.88	29.25	31.50
2 Load-factor 42.5 per cent	41.35	30.80	28.69	28.17	26.10
3 Load-factor 32.0 per cent	40.07	27.37	23.95	22.73	23.40

Table IX shows that for a hydraulic cost of $100 and an annual steam cost of $10, the development must be carried beyond 0.5 sec-ft. per square mile, for any load-factor except the 64 per cent. That is to say, that a development for a stream flow of 0.5 sec-ft., under the assumptions made, can not compete with the steam supply, at any except a very high load-factor. If, however, the annual charges on the steam plant are taken at $15, then the development of 0.5 sec-ft. is cheaper than the steam plant at all of the load-factors, the point of equal costs being somewhere between 0.25 and 0.5 sec-ft.

If the hydraulic cost is assumed at $150 and the fixed charges at $10 then no hydraulic development is economical up to 1.0 sec-ft., with the possible exception of a load-factor of 64 per cent with a development of 1.0 sec-ft. which gives the total cost substantially the same as the steam cost. If, however, the hydraulic cost is taken at $150, and the annual steam cost at $15, the combined development might be economical at 1 sec-ft., but not at the low discharges, generally speaking.

The gist of the matter is that on the assumptions made, which

are, as far as I am able to tell, reasonable, the hydraulic development must be carried to a very much higher point of stream-flow than is usually assumed and with a greater percentage of reserve plant, in order that the combined plant shall show any savings in comparison with the steam supply.

These three examples are all for plants with pondage. To show the difference when there is no pondage, Example IV is given, the same general assumptions are made as in Example II, the intermediate load-factor being taken. The cost of the hydraulic plant is taken at $100 per kilowatt of maximum capacity, as in Table II; this corresponds to $100 per kilowatt for a development of

$$Q_m = 0.5/0.45 = 1.18 \text{ sec-ft. as maximum flow.}$$

With these assumptions, Tables X and VII are directly comparable; the difference in total costs is due entirely to the lack of pondage and consequent increased cost of the steam supply. For example, for 0.25 sec-ft., the cost of the steam supply with pondage is $3.20 per kw., without pondage $8.96, making a difference of $5.76 per kw. For 0.75 sec-ft. the difference is $3.94 per kw. The difference in cost increases as the cost of the steam supply increases. The percent-deficiency is calculated from the percent-load curve, in the manner explained above.

EXAMPLE IV: No pondage. Load curve of Fig. 12. Same data as Example II except that $C_h = \$100$ for $Q_1 = 0.5/0.425 = 1.18$ sec-ft. That is, the cost per kilowatt of plant capacity is taken the same, viz. $100, for the same maximum power.

TABLE X.

1. Flow for average power, $Q_m \times f$, sec-ft.	0.25	0.50	0.75
2. Flow for maximum power, Q_m	0.59	1.18	1.77
3. Ratio of capacity, $Q_m/1.18$, =	0.50	1.0	1.50
4. Ratio minimum/maximum-flow, $0.1/Q_m$	0.17	0.085	0.06
5. Steam plant capacity, p_s, $\{1.00 - (4)\}$	0.83	0.915	0.94
6. Per cent-deficiency, p_d	5.80	15.5	25.5
7. $11.40 $\times p_s$	$0.66	$1.77	$2.90
8. $10 $\times p_c$	8.30	9.15	9.40
9 $A_s = (7) + (8)$ = Steam cost	8.96	10.92	12.30
10. $A_h = \$15\ k_r$ = Hydraulic cost	25.00	15.00	11.70
11. $S = A_s + A_h$ = Total Cost	$33.96	$25.92	$24.00
The increment to be added to line (11) for			
12. $C_h = \$150$ is	$11.70	$7.00	$5.48
13. $c = \$15$ is	4.15	4.58	4.70
And therefore for			
14. $C_h = \$100$: $c = \$15$, S is	38.11	30.50	28.70
15. $C_h = \$150$: $c = 10$, S is	45.66	32.92	29.48
16. $C_h = \$150$: $c = \$15$, S is	49.81	37.50	34.18

Example V shows the effect on the total cost of a different division between the fixed and variable portion of the hydraulic cost. The tables above were based on a division of 67 and 33 per cent; but Table XI, for the same data as Example II, assumes a division of 50 and 50 per cent. This change increases the total cost for flows greater than the assumed basic flow of 0.5 sec-ft. and diminishes it for flows less than 0.5 sec-ft.

EXAMPLE V: To show the effect of different ratios of fixed to variable cost of hydraulic plant. Data of Example II, but assuming

$$k_r = 0.5/r + 0.5$$

This change does not in any way affect the steam-reserve costs and is independent of the load curve.

TABLE XI.

1. Q_r, sec-ft.	0.25	0.50	0.75	1.00
2. $Q_r/0.5 = r$	0.5	1.0	1.5	2.0
3. k_r for $a = 0.5$	1.50	1.00	0.83	0.75
4. \$15 k_r for $a = 0.5$	\$22.50	\$15.00	\$12.40	\$11.25
5. \$15 k_r for $a = 0.67$ (Table VII)	25.00	15.00	11.70	10.00
6. Difference (4) − (5)	−2.50	0.0	0.70	1.25
This amount is to be added to the costs of Table VII for C_k = \$100.				
7. For C_k = \$150, there is to be added $\left\{\frac{22}{15} \times (6)\right\}$	−\$3.66	0	\$1.02	1.84

For $Q_r = 0.25$, and all flows less than 0.5, the difference is negative, to be subtracted.

Example VI shows the effect on the annual cost of differences in the hydraulic characteristics of the stream; it gives a comparison between the Potomac, for which the percent deficiency curve is given in Fig. 7 and the Susquehanna, as applied to a load of 64 per cent load-factor. The table shows that the costs for the Potomac are \$1 to \$2 per kilowatt more than the Susquehanna under identical conditions, except in respect to stream flow.

EXAMPLE VI: Conditions of Example I. Applied to the Potomac, as in Fig. 7. The only difference is that for any given flow the deficiency is greater for the Potomac, which means more energy from the steam plant

TABLE XII.

1.	Q_r ..... sec-ft.	0.25	0.5	0.75	1.00
2.	Percent-deficiency, Susquehanna, (Fig. 6)	2.7	10.4	18.1	25.4
3.	Percent-deficiency, Potomac, (Fig.7)	2.7	16.6	28.2	37.8
4.	Difference (3) — (2)	0	6.2	10.1	12.4
5.	Difference in cost, for Fig. 9	0	$1.02	$1.67	$2.05

That is, these sums added to all the cost of Table VI will give the cost for the Potomac, for the same assumptions of costs of plant and operation.

Example VII shows the method of calculating the cost of providing a reserve plant down to different assumed conditions of low discharge. The rated capacity of the development is taken at 0.75 sec-ft. and the total annual cost for a steam plant insuring the delivery down to 0.1, 0.25, and 0.5 sec-ft. respectively is given. This brings out the heavy cost of the steam reserve for the last few per cent of the power deficiency. A difference of $3.10 per kilowatt between the cost for steam plant down to 0.25 sec-ft. and down to 0.1 sec-ft. means a cost of 3.1 cents per kw-hr. for the energy delivered by that portion of the plant necessary to insure this deficiency. It may well be that the penalties incurred by failure to make delivery between these limits would be much less than the cost of insuring it.

EXAMPLE VII: Cost to provide steam reserve for various assumed minimum flows.

Load-curve of Fig. 12: with pondage. Development for $Q_r = 0.75$ sec-ft.

TABLE XIII.

1.	Reserve plant down to flow Q_0 = ...	0.1	0.25	0.5
2.	Ratio, $Q_0/0.75$	0.13	0.33	0.67
3.	p_e (Fig. 6)	0.00	2.7	10.4
4.	p_e for $Q = 0.75$ sec-ft.	18.1		
5.	Difference (4) — (3)	18.1	15.5	7.7
6.	p_c (Fig. 12) for $Q_0/0.75$	0.63	0.35	0.17
7.	$11.40 × (5) = ...	$2.06	$1.76	$0.88
8.	$10 × p_c (line 6)	6.30	3.50	1.70
9.	A_s = Cost of steam reserve, (7) + (8)	$9.36	$5.26	$2.58
10.	A_h, from Table VII	11.70	11.70	11.70
11.	Total $A_s + A_h = S$	$20.06	$16.96	$14.25

Increased cost to carry reserve down to 0.1 from 0.25. sec-ft.:—
Difference in A_s = $3.10
Energy supplied, 2.7 per cent × 3700 = 100 kw-hr.
Cost per kw-hr., 3.10 cents.

These examples are given merely to illustrate the application of the method to different conditions of stream-flow and load curves. It is not pretended that the results given are applicable generally and the object of the paper is not to give conclusions but simply to develop a method of handling the problem and to give certain illustrations based on reasonable data. I believe that the examples shown will be sufficient to enable any engineer to follow the method substituting the data of his own case for those given. I hope also that I have taken at least one step toward a logical method of procedure for the solution of this problem.

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THE COST OF ELECTRICITY AT THE SOURCE

BY H. M. HOBART

ABSTRACT OF PAPER

The Stott-Gorsuch method is applied to the determination of the cost of manufacturing electricity in a 60-cycle station of 100,000 kilowatts installed capacity. The results correspond to the assumption that such a station is capable of delivering from 350,000,000 to 700,000,000 kelvins per annum for load factors ranging from 0.50 to 1.00. For unity load factor the cost of three-phase electricity at the outgoing cables ranges from 0.65 cent per kelvin with coal at $5.00 per ton, down to a matter of 0.20 cent per kelvin for fuel of negligible cost. A method is indicated for tracing through the increase in the cost of the electricity at later stages of its journey from the source to the consumer.

BY THE time electricity is delivered on the premises of small consumers such considerable costs will have been incurred that the price admitting of any profit can rarely be less than somewhere from two cents to eight cents per kelvin[1]. The original cost of manufacturing in bulk, however, is a far less amount. It is desirable that this should be more generally realized, as it indicates the great field for electricity for large manufacturing enterprises which can be located near the source of electricity supply. Under favorable conditions electricity can be manufactured in bulk at a cost of the order of 0.25 to 0.40 cent per kelvin.

In an address delivered by Ferranti[2] in 1910, the proposition was formulated that, on certain assumptions, a station equipped with ten 25,000-kw. generating sets could be built at a total cost of £7 ($35) per kilowatt. I have made estimates which indicate $35 per kilowatt to be sufficient for a 100,000-kw. station equipped with five 20,000-kw., 1800-rev. per min., steam-turbine-driven, three-phase generators and all the machinery required in such a plant. As a matter of interest it may be stated that the outlay for the turbo-generators, cables, exciters and switchgear is covered by 30 per cent of this $35 per kilowatt. (In and near large

1. In this paper the term kelvin is employed instead of the term kilowatt-hour.

2. *Jour. Inst. Elec. Engrs.*, Vol. 46, pp. 6.

cities this sum would be insufficient, since the outlay for land and buildings would then usually be at least $10 per kw.)

The following estimate for the cost of electricity when manufactured in such a station, will be based on the Stott-Gorsuch method,[3] in accordance with which the total cost is considered as made up of three components. These three components are:

1. Production Costs.
2. Investment Costs.
3. Administration Costs.

I shall divide the Production Costs into two items, A and B.

Item A[4] relates to all components of the Production Costs except fuel. Item B relates to the cost of fuel. While A will vary by a small amount with the load factor, I shall neglect this variation and take:

Item A = $700,000[5]

Item B: In estimating the annual outlay for fuel we must first have data for the over-all efficiency of the station. From an examination of the thermal efficiencies of turbo-generating sets and steam raising plant, one would be led to expect over-all efficiencies from the coal to the outgoing cables ranging from at least 18 per cent for unity load factor down to at least 16 per cent for a load factor of 0.50. But reasoning from the results actually obtained in practise, it is not considered that it would be conservative to take values higher than the following:

Load factor	Over-all efficiency
1.00	15 per cent
0.75	14 " "
0.50	13 " "

Assuming the maximum load from our 100,000-kw. station to be 80,000 kw., the annual output for these three cases is:

Load factor	Annual output in mega-kelvins.
1.00	700.
0.75	525.
0.50	350.

3. Trans. A. I. E. E., Vol. XXXII, 1913, p. 1619.

4. Item A covers wages, repairs, lubricants, water, supplies, etc.

5. It is believed that an analysis will show this value to be reasonably representative for Item A and that in so far as it errs it is in the direction of being conservative. It will cover any investment costs associated with the water supply, such as cooling towers when required.

The energy in the coal consumed per annum amounts to:

Load factor	Mega-kelvins of energy in the coal
1.00	4660
0.75	3750
0.50	2690

The estimates may be based on coal with a calorific value of 12,000 B.t.u. per pound.[6]

1 kelvin equals 3411 B.t.u. Consequently each (2000-lb.) ton of coal contains

$$\frac{12,000}{3411} \times 2000 = 7000 \text{ kelvins}$$

The quantity of coal burned per annum is as follows:

Load factor	Quantity of coal burned per annum
1.00	667,000 tons
0.75	535,000 "
0.50	384,000 "

In the following table are set forth the outlays for fuel on the basis of 50 cents per ton and $5 per ton.

Load factor	Annual Outlay for Fuel	
	50 cents per ton	$5 per ton
1.00	$334,000	$3,340,000
0.75	268,000	2,680,000
0.50	192,000	1,920,000

The above amount represents Item B, the fuel component of the Production Costs per annum. We have already stated that for the remaining component of the Production Costs, (Item A), we shall take the constant value of $700,000.

6. The results of this investigation are presented in such form as to permit of ready modification to correspond to the use of fuel of other calorific values than 12,000 B.t.u. per pound.

Adding A and B we obtain the total Production Costs set forth in the following table.

Load Factor	Production Costs per Annum.	
	Fuel at 50 cts. per ton	Fuel at $5 per ton
1.00	$1,034,000	$4,040,000
0.75	968,000	3,380,000
0.50	892,000	2,620,000

In terms of cents per kelvin, the above Production Costs are:

Load Factor	Production Costs per kelvin	
	Coal at 50 cts. per ton	Coal at $5 per ton
1.00	0.148 cent	0.576 cent
0.75	0.184 "	0.645 "
0.50	0.254 "	0.750 "

We now come to the second component of the total cost, namely the Investment Costs. At $35 per kilowatt the initial cost of the 100,000-kw. station is:

$3,500,000.

This is sufficient to cover engineering supervision and contingencies.

On the basis of:

Interest	5.0 per cent
Rates, taxes and insurance	3.0 per cent
Amortization	4.6 per cent
Total annual charges on investment[7]	12.6 per cent

we arrive at an Investment Cost per annum of

$$0.126 \times 3,500,000 = \$441,000.$$

In terms of cents per kelvin the Investment Costs are:

Load factor	Investment costs per kelvin
1.00	0.063 cent
0.75	0.084 "
0.50	0.126 "

7. For other capital costs per kw. and for other rates and other depreciation assumptions the corresponding annual investment costs are readily deduced. Those adopted in this investigation would appear representative for such a station.

As to the final item in the total cost, namely the Administration Costs, let us distinctly limit this item to the bulk manufacturing undertaking. Let the *marketing* of the electricity be separately handled by another undertaking. With this understanding, an allowance of $100,000 per annum is reasonable for the Administration Costs. This provides for an administrative organization simply concerning itself with manufacturing the electricity and delivering it at the outgoing cables.

Per kelvin, this amounts to:

Load Factor	Administration Costs per kelvin
1.00	0.014 cent
0.75	0.019 "
0.50	0.029 "

The Total Costs are worked out in the following table, in which Production Costs are indicated by I, Investment Costs by II, and Administration Costs by III.

Load Factor	Component and Total Costs in Cents per kelvin	
	Coal at 50 cents per ton	Coal at $5 per ton
1.00	I = 0.148 cent II = 0.063 " III = 0.014 " Total = 0.225 cent	I = 0.576 cent II = 0.063 " III = 0.014 " Total = 0.653 cent
0.75	I = 0.184 cent II = 0.084 " III = 0.019 " Total = 0.287 cent	I = 0.645 cent II = 0.084 " III = 0.019 " Total = 0.748 cent
0.50	I = 0.254 cent II = 0.126 " III = 0.029 " Total = 0.409 cent	I = 0.750 cent II = 0.126 " III = 0.029 " Total = 0.905 cent

These total costs are plotted in Fig. 1 with cost of coal as abscissas. They are plotted in Fig. 2 with load factors as abscissas.

For water power stations, if there is no charge for the water, and if the total investment can be kept as low as $35 per kilowatt, the lowest curve in Fig. 2, (*i.e.* the curve for fuel at a negligible cost per ton) may be taken as affording a fair indication of the cost of electricity at the source.

This investigation has been based on the assumption that the electricity delivered from the station is of unity power factor. For lower power factors the total cost of the electricity will be higher. Professor Arno of Italy has devoted a great deal of study to the influence of the power factor on the cost of electricity and has arrived at the conclusion that for practical purposes the cost may be taken as proportional to two-thirds of the true output, plus one-third of the apparent output (*i.e.*, the true output divided by the power factor). Thus if we take the case of our 100,000-kw. station when the load factor is 0.50, we have seen that the cost, with coal at 50 cents per ton, is

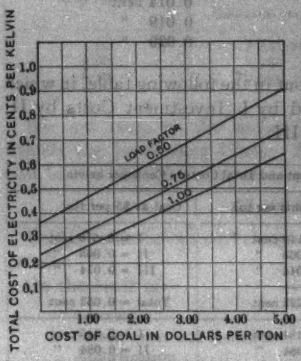

FIG. 1

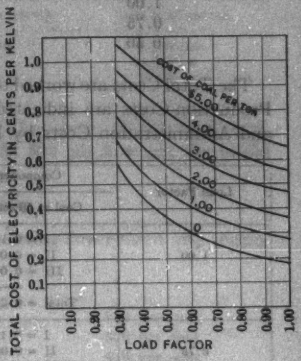

FIG. 2

0.409 cents per kelvin for unity power factor. If the load is of 0.80 power factor the cost by the Arno rule will be:

$$\left(0.667 + \frac{0.333}{0.80}\right) \times 0.409 = 0.444 \text{ cent per kelvin}$$

Prof. Arno's rule may be regarded as a useful approximation for representative conditions. The application of the present method of analysis to outputs of different power factors would show that no such simple rule would suffice. The influence of the power factor would for instance be much affected by the ratio of the cost of fuel to the total costs, and would be different with different load factors.

Indeed, a similar general criticism applies to Mr. Stott's nevertheless useful approximate rule that the Production Costs may be taken as inversely proportional to the fourth root of the load factor. There may be wide deviations from such a rule occasioned by extremes in cost of fuel and in other conditions.

Furthermore the costs which we have worked out have related to delivering 60-cycle three-phase electricity at the pressure at which it is generated, say 10,000 volts. If it is to be stepped up to, say, 100,000 volts, to be transmitted in bulk to a distance, then the cost at the high-pressure side of the step-up transformers may be obtained as follows:

Let us take the case of a load factor of 0.50 and coal at 50 cents per ton. Let the power factor be unity. The cost under these conditions has been estimated to be 0.409 cent per kelvin. We shall require to provide step-up transformers with an aggregate capacity of 100,000 kw. Their cost would be of the order of $2.70 per kilowatt, making a total outlay of $270,000. The annual outlay for interest, rates, taxes, insurance, amortization, repairs and attendance may be taken as

$$0.15 \times 270{,}000 = \$40{,}500.$$

The annual output from the station when the load factor is 0.50 has already been estimated to be

350 mega-kelvins.

Taking the annual over-all efficiency of the transformers as 97.5 per cent, the output from the transformers is

$$350 \times 0.975 = 341.5 \text{ kelvins.}$$

Therefore the step-up transformer costs, per kelvin delivered from them, are

$$\frac{4{,}050{,}000}{341{,}500{,}000} = 0.012 \text{ cent}$$

The total cost per kelvin delivered from the step-up transformers is

$$\frac{350.0}{341.5} \times 0.409 + 0.012 =$$

$$0.419 + 0.012 = 0.431 \text{ cent.}$$

Thus the cost has increased 5.5 per cent by the time the pressure has been stepped up. This paper is entitled "The Cost of Elec-

tricity at the Source." By similar processes, however, the increases in cost can be traced right through to the consumers' premises.[8] But the reasoning becomes very involved when we arrive at the stages where the electricity is no longer carried in bulk. At these stages questions relating to appraisements of value, diversity factor, ethics and commendable sentiment render it impossible to arrive at any precise method which can be conclusively demonstrated to provide for equitably distributing the total costs amongst the various consumers.

8. In a paper entitled "The Relative Costs and Operating Efficiencies of Polyphase and Single-Phase Generating and Transmitting Systems," Hobart, TRANS. A. I. E. E., Vol. XXXI, 1912, p. 115, the author has applied this method of studying in a certain case the growth of the cost of electricity, commencing with the outgoing cables from the generating station and concluding with the cost as delivered from the distant substations.

DISCUSSION ON "THE COST OF ELECTRICITY AT THE SOURCE" (HOBART), NEW YORK, FEBRUARY 26, 1914.

J. W. Lieb, Jr: I am sure that under the conditions obtaining in our larger cities the figure given by the author, of $35 per kilowatt of capacity, will not cover the real estate and buildings of a character to satisfy local conditions. The sum of $35, even if otherwise adequate, which I doubt, would allow the merest shell of a building rather than such a structure as it would be necessary to provide to house a plant of the capacity indicated by the author.

H. R. Summerhayes: I ask Mr. Hobart how many days' coal storage is provided for under his plan. In these days of coal strikes and interruptions to transportation it seems necessary to provide a large acreage of land to store a large amount of coal. Such a station ought to require quite a large area for that purpose.

H. W. Buck: There is one advantage which the steam plant has in this comparison. As a rule, the water power plant is many miles from the point at which the power is applied, and the cost of transmission lines, substations, etc., must be added. On the other hand, the steam plant, as a rule, can be located practically at will, and as near as possible to the center of load. This also applies to operating costs on the transmission system, which the steam plant will not have to so great an extent.

Frederick A. Scheffler: I hope that the author of this paper will be more specific in giving us exact data as to how he arrives at $35 per kilowatt for the cost of constructing a complete 100,000-kw. station.

I would like to know what size boiler units he proposes to use, whether he will use steam turbines, and if so, what size units, working steam pressure, superheaters, if any, and degree of superheat, at what rating the boilers will be operated and what kind of stokers will be used, whether under-feed or otherwise, and whether the cost covers economizers.

I have in mind a plant which is being constructed in the West at the present time, of an ultimate capacity of 120,000 kw. The company which is building this plant feels that if it can construct the station, using six 20,000-kw. turbines and twelve 2400-h.p. (nominal rating) boiler units, with superheaters for 200 deg., and operating the boilers at 200 per cent of rating when necessary, and the cost does not exceed $55 per kilowatt complete, it will have a very reasonable and inexpensive station, considering its construction, which is to be of the very best throughout.

H. L. Wallau: I have only one criticism to make of this paper, and that is the figure of $35 per kilowatt. That figure has been qualified in this discussion, and it has been qualified as presented by Mr. Hobart. However, in a city such as Cleveland is, the tendency will be for the engineers of the municipality to say, just as soon as a figure of $35 per kilo-

watt is published in an Institute paper, that it must be pretty close to the actual cost. Apparently the way they figure cost in Cleveland in a municipal undertaking, is to take the figures, for instance, published in the Institute PROCEEDINGS for a 300,000-kw. plant, and say, "If they can do that in a 300,000-kw. plant we ought to be able to do practically that in our 15,000-kw. plant", and as a result they have published a schedule of rates, with a maximum rate of three cents and a minimum rate of one cent. I believe on last Tuesday they got ready to pass a maximum rate ordinance of three cents, to which they expect us to conform. I think for these reasons, when a statement is made, and a figure is published, that it should be carefully qualified, because the tendency towards municipal ownership is growing rapidly in this country, and the analysts are, I believe, making some very grave errors in their calculations.

H. B. Alverson: The load factors given are too high for the usual existing conditions, and while it may not be the intention in the paper to give exact figures, I believe the load factor which will occur in practise will be nearer to 35 or 40 per cent than to 50 per cent. In such cases the cost per kilowatt-hour would rise somewhat higher in proportion than the figures given. Without going into the calculation of the proportion of costs based on the load factor, I think the average experience is that it is very much higher than that which is given in the paper.

O. K. Harlan: Regarding the matter of depreciation, it might be of interest to note that a few weeks ago, before the American Society of Heating and Ventilating Engineers, a paper was presented giving something of the life history of quite a number of the old electric lighting steam-driven plants in this city, and the matter of depreciation was dealt with in that paper. It traces the history of the very earliest installations, including the first steam-driven electric dynamos which were operated in the city. One of the old ones is in the Mills building, and a number of others are down-town, near it. The depreciation was shown to be quite a variable factor; of course, some generators will deteriorate faster than others, and the matter of economy and efficiency is quite an item also; that is to say, some of the more recent generators may be of so much higher efficiency that it is worth while to discard a really good working machine in order to put in a more modern machine of higher efficiency. However, this paper shows that a number of these earlier plants have had a useful life of twenty years; some are really working today, which were installed twenty years ago—but the matter of depreciation, while it is a very interesting subject, is really somewhat intricate, and there are a good many factors entering into the final decision.

H. C. Abell: If Mr. Hobart means the $35 to cover the cost of machinery, water facilities for a plant of that size, storage requirements, working capital, supplies, cost of financing the undertaking, and all the incidental expense, I think unquestionably he used the wrong multiplying factor to arrive at the figure given, which I consider too low.

Another thing which attracts one's attention is the five per cent interest figure used by Mr. Hobart. I do not know of any money source which could be induced to provide funds for a power-generating plant on a five per cent basis.

I suppose amortization placed at 4.6 per cent is a depreciation fund, for a power plant is usually not amortized, but is a continuous business where the owners have to provide funds continuously for new construction after the plant once starts. Amortization is entirely different from depreciation; the two terms should not be confounded.

A. H. Kruesi: With regard to depreciation, I believe obsolescence often cuts a much larger figure than depreciation due to wear and tear. I am associated with a large steam-turbine power plant built eleven years ago. The stokers and their auxiliary equipment are now being scrapped because they are obsolete, though not worn-out. A number of boilers installed seven years ago are also being scrapped because they are of a type no longer manufactured and the allowable working pressure has been reduced, so that they have become unsuitable to their purpose. The entire switching equipment is being replaced after eleven years' use because the plant has grown and it is no longer adequate for the amount of power behind it. I agree with the criticism of Mr. Hobart's paper, on the score of his capital cost charges. I do not see how they could possibly be figured at less than 15 per cent.

V. Karapetoff: Mr. Hobart's paper has been criticised on account of the specific numerical data given in it. I know from certain experiences in court testimony that outsiders are only too liable to ascribe to the Institute any data published in its PROCEEDINGS, in spite of the well-known fact that the Institute is not responsible for opinions expressed by its individual members. To me, personally, Mr. Hobart's paper is exceedingly interesting and instructive in giving a concrete method of calculation. If he had chosen to use letters, instead of numerical values, I am afraid the paper would be exceedingly difficult to follow, but then it would have been of greater general interest, as any one could substitute numerical values for his particular problem and the above criticism would be obviated.

I was surprised at the statement that the outlay for the turbo-generators, cables, exciters, switch gear, etc., amounts to only 30 per cent of the total cost of the generating station. It seems to me that engineers in this country ought to be more interested in the Thury system of generation, which, so far, has been mainly applied to hydroelectric stations, but lately was chosen in London for underground distribution from a steam plant. The principal advantage of the Thury system is that not only the cables themselves cost much less, but also the generating station is lower in cost; while the generators themselves are more expensive, the cost of auxiliary apparatus is much lower. If one goes into a station like the Northwestern station in Chicago, it is the auxil-

iaries which strike one's eye, and it is the auxiliaries which occupy the most room and apparently seem to cost the most.

G. L. Knight (by letter): The author of this paper states that a 100,000-kw. steam station, consisting of five 20,000-kw., 60-cycle, 1800-rev. per min., three-phase turbo-generators, together with all the apparatus, both steam and electric, required for the operation of such a plant, can be built in this country for an over-all charge of $35 per kilowatt.

This paper, being presented before the A. I. E. E., presupposes in the absence of contrary statement that the figures given represent American practise, but in replying to the discussion on his paper in the meeting of February 26, Mr. Hobart defended his estimate by the following figures taken from estimates of plants constructed in England:

Turbo-generators, including exciters and switch gear	$10.50 per kw.
Steam raising plant	8.50 " "
Condensing equipment	5.00 " "
Building	8.00 " "
	$32.00 per kw.

This leaves only $3.00 for the rest of the charges, which must include land, general engineering and construction expense other than that included in the items as given, also all overhead charges during the construction period.

In place of the figures set down by Mr. Hobart, I would give the following as minimum values, and while they will vary greatly according to the conditions a plant must meet, the total cost per kilowatt will be often much nearer $75.00 than the figure given.

Building		$10.00	
Turbo-generators, including exciters	$12.50		
Switch gear	3.00		
		15.50	
Steam plant			
Boilers	6.00		
Stokers	2.50		
Flues and piping	2.00		
Coal and ash handling equipment	1.50		
		12.00	
Condensing equipment			
Condensers and pumps	3.00		
Condensing tunnels	2.00		
		5.00	
Engineering, drawings, supervision			42.50
and other overhead expenses, 15 per cent			6.35
Allowance for piecemeal construction and contingencies, 15 per cent			6.35
			$55.20

To those of us in the employ of public service companies this paper seems at least ill-advised. Regulating bodies and the advocates of municipal ownership are constantly challenging our capital costs, and when a company's books show a cost of $50 to $75 per kilowatt for a new plant (and older ones will be even higher), papers such as this are quoted in attempts to prove such costs excessive.

In such cases it is assumed, by those who do not know the Institute rule, that having accepted such a paper for presentation at a meeting, the Institute must have passed on it as being reasonable.

I think Mr. Hobart should have stated that his whole case rested on English figures, and I am inclined to believe that even in England no plant has ever been completed which, when all charges were accounted for, came within his figure at $35 per kilowatt.

Frederick G. Strong (by letter): Permit me to say a word in behalf of our water powers; they seem to have very few friends among those who have discussed Mr. Hobart's paper.

I remember a paper by Dr. Emory, in which the general statement was made that where the cost of water power development exceeded $150 per horse power a steam-driven plant would be advisable where good coal could be obtained at about $4 per ton. We have heard, periodically, that a slight increase in efficiency or a slight decrease in the cost of steam-driven machinery, would cause the water powers to be abandoned, or left undeveloped.

We have seen a marked increase in steam efficiency in the past ten years and a marked decrease in cost per kilowatt, due to increased size of units and increased speed and activity of material, but the water powers are still in use. None have been abandoned, and plans are being formulated for the development of many more.

The theory that water powers should be abandoned, or left undeveloped when they show a greater cost than equivalent steam-driven stations, does not seem correct, and I believe the time is not far distant when we will develop every available water power, to the end that the coal supply may be conserved as much as possible.

Undoubtedly the water powers at Holyoke, and Lowell, and Lawrence, and Manchester have cost far more than equivalent steam power, but if those investments were annihilated, does any one believe that the power would be left undeveloped?

In the energy of falling water Nature has not by any means given us something for nothing, but it is doubtful if we may expect a nearer approach.

H. M. Hobart (by letter): I shall deal with the contributions to the discussion of my paper in the order in which they were made.

As to the first comments which were made by Mr. Lieb, it

would appear that his intention is to supplement my paper and emphasize the importance that it should not be construed as applying to stations located in or near large cities. It was clearly shown in my paper that I referred to a station located with especial reference to low cost of land, abundance of circulating water and low price for fuel. This necessarily locates the station at some situation where architectural effect is absolutely out of place. In the recent report made to the London County Council by Messrs. Merz and McLellan, it is pointed out that in modern plants "the power house tends more and more to become a metal structure for housing the machinery rather than an actual building in the usual sense." The savings which can be effected under the conditions which I describe for my plant are inapplicable to a power house located in our larger cities, and I am glad that Mr. Lieb took the occasion to emphasize this point. Furthermore, in city plants supplying electricity for all sorts of purposes to a large community there must be large investments for duplicate switch equipments and for supplying large numbers of feeders. This inevitably runs up the cost, as it does also the need for economizers, which are justifiable under these circumstances, since the price of fuel is relatively high. It was expressly stated in my paper that no outlay for transformers was included, and further, that the estimates related to 60-cycle generating sets. These sets were only five in number, of the most modern type, and were for a rated speed of 1800 rev. per min. In city stations it is often necessary to supply, not only 60-cycle electricity, but also 25-cycle electricity, and furthermore, the stations will usually be found to be equipped with more than one size of generator. Moreover, the average rating of all the generators in the station is usually much below that of the 20,000-kv-a. units on which I based my estimates, and they are driven at lower speeds, as a consequence of which they are larger, more expensive in first cost, more wasteful of fuel, and a greater outlay is required for the attendance upon them. When a given aggregate output is delivered from ten small units, as against five large units, the outlay for wages in the station is decidedly greater. Mr. Lieb considers that the real estate and buildings for a station in our larger cities would not be covered by $35 per kilowatt of capacity. Taking it at $40, and including an appropriate allowance for the increased outlay for switch gear and for economizers and transformers, then, with an allowance for engineering and contingencies amounting to 10 per cent of the total, we arrive at over twice the capital outlay per kilowatt installed that would have been necessary on the same scale of prices for a station complying with the conditions set forth in my paper.

In the matter of Mr. Summerhayes's suggestion that in these days of coal strikes and interruptions to transportation, it seems necessary to provide a large acreage of land to store a large amount of coal, I would point out that with such locations as that clearly contemplated in my paper, the land could not rea-

sonably be taken as costing more than $200 per acre. On this basis, the outlay for a site of 50 acres would only amount to $10,000, which is less than three-tenths of one per cent of the total capital outlay for this 100,000-kw. generating station. Mr. Summerhayes evidently also had in mind the conditions in large cities, far away from the mines, and I quite agree with him that under these conditions the point which he mentions would be one requiring careful attention.

I fully agree with the point which Mr. Buck makes that the steam plant has the advantage over the waterpower plant, that it may sometimes be located quite near to the center of the load, thus minimizing the costs in transmitting the electricity to the customers. However, I dealt with "The Cost of Electricity *at the Source*" and pointed out that by locating a generating station where the conditions as regards fuel and water supply and cost of land are favorable, electricity can be manufactured for a low price and that industries, the cost of whose product depends largely on the outlay for electricity, would be well advised to realize and take advantage of such possibilities.

I am pleased to be able to comply with Mr. Scheffler's request for more specific data as to how I arrive at the cost of the complete 100,000-kw. station. This is set forth in the following table:

	Five 20,000-kw. units
I—Turbo-generators, exciters, cables and switch gear, but exclusive of step-up transformers	$10.50
II—Boilers, superheaters, furnaces, and stokers, but exclusive of economisers, pumps and piping	9.00
III—Condensers, exclusive of pumps, piping and tunnels	2.50
IV—Pumps, piping, tunnels, valves and traps	1.50
V—Land and all buildings and structures, including machinery foundations, stacks, bunkers and conveyers	8.00
VI—Engineering and contingencies (10 per cent)	3.50
Total cost per kilowatt	$35.00

Mr. Wallau also points out how important it is that the conditions under which such figures can be reached should be clearly stated. I welcome Mr. Wallau's assistance in helping me to point out the distinction between plants of the size and character which I am discussing in the paper, and such relatively small plants as those to which he refers.

Regarding Mr. Alverson's comments, I show in the curves in Fig. 2, on page 396, the cost of electricity for all load factors down to 0.30. It may, however, be of interest to point out that the application of electricity to chemical and certain other industries often permits of much higher load factors than have, until recently, been at all customary, and that decided commercial importance attaches to a knowledge of the costs under such conditions of high load factor. Such applications are usually only practicable when the cost of electricity is very low, and in the

near future we shall certainly see such industries purposely located where conditions are favorable as regards plentifulness of water and low cost of fuel and land.

Mr. Harlan makes some interesting suggestions. He calls attention to 20 years as a reasonable life for electrical machinery in many cases. My figures for the investment cost are based on an equivalent life of 15 years.

The next two contributors to the discussion of my paper were Messrs. Abell and Kruesi. It is the opinion of both of these gentlemen that my investment costs are a little too low, Mr. Abell's criticism being that funds can rarely be obtained for a power generating plant at so low a rate of interest as five per cent, and Mr. Kruesi emphasizing the importance of the obsolescence factor. All engineers realize the difficulty of equitably assessing the investment costs, owing to the impossibility of predetermining the obsolescence factor and the great difference in the financial standing of companies embarking upon electricity supply enterprises. I believe that the figures on which I have based the annual investment charges are representative for the case under discussion, but it is obviously important to apply a safety factor which should be inversely proportional to the financial standing of the companies.

I am interested in Prof. Karapetoff's suggestion that my paper would have been of greater general interest had I chosen to employ letters instead of numerical values. My own experience is, however, that the paper would not have attracted attention. It is my experience that papers rarely fulfil any useful mission unless they stimulate discussion.

Mr. Knight puts forward an interesting alternative estimate, regarding which I should like to offer the following comments. For "turbo-generators, including exciters," Mr. Knight allows $12.50 per kilowatt. For "turbo-generators, exciters, cables, and switch gear" I gave the figure of $10.50 per kilowatt. For a city station with its more elaborate provision for switch gear and its large number of feeders, the equivalent allowance would be $11.50 per kilowatt were five 20,000-kw., 60-cycle, 1800-rev. per min., unity power factor turbo-generators to constitute the equipment. If we turn to Fig. 17 in Messrs. Stott, Pigott and Gorsuch's paper* entitled *Present Status of Prime Movers*, presented at the Detroit Convention, June, 1914, we find $7.50 per kilowatt taken as the "average" cost of a 20,000-kw., 60-cycle, 1800-rev. per min. turbo-generator. This would seem to indicate that my figures are conservative for large plants favorably located.

As regards the other items, Mr. Knight's estimates do not differ materially from my own, except that he allows 30 per cent for "engineering, drawings, supervision and other overhead expenses, piece-meal construction and contingencies" as against my allowance of 10 per cent for "engineering and contingencies." I quite agree that such items may run up to large values and that for each case they must be separately considered.

*See Part II of this volume of TRANSACTIONS.

The last contribution to the discussion is by Mr. Strong and is to the effect that waterpower should—and will—be developed irrespective of the relative capital and operating costs of the investment, as compared with the equivalent undertaking employing turbo-driven generators. One of the objects which I had in view in writing my paper was to call attention to the liability of misapplication of capital. Large amounts are often invested in waterpower developments running much above $100 per kilowatt installed and in some of these cases it could be demonstrated that the greater capital charges more than offset the elimination of fuel costs. Often a steam-turbine station at a favorable site would represent a better investment. But there is the liability that any consideration of a steam-turbine station will be dismissed after very superficial calculations, in the mistaken belief that the investment for the steam station will necessarily be excessive. Fifteen years ago (before the advent of the steam turbine) the case was much more favorable for waterpower as compared with steam.

It is equally desirable to call attention to the related danger that the high efficiency of the internal combustion engine will attract capital, notwithstanding that the generating sets alone will cost at least $60 per kilowatt and even the fuel cost will be as great with the internal-combustion engine as with the steam turbine with oil at 2½ cents per gallon and coal at $3.00 per ton.* The outlay for attendance, lubrication, and repairs will be much greater with the internal combustion installation. The misdirection of capital in this way would be checked by the more general realization of the low investment cost associated with steam turbines.

In conclusion I should like to take the opportunity to discuss briefly the factors which have contributed to the rapid progress which has been made toward decreased cost of electricity. There has been of recent years rapid progress in the direction of increased efficiency of prime movers. This has been accelerated by the use of individual sets of very large capacity. Not only have these sets relatively high efficiencies, but the investment cost per kilowatt is relatively low. It is well known that the steam consumption of modern steam tubines is much less than ten years ago, consequently a given capacity of steam raising and condensing plant will now provide steam for a station of much greater capacity than formerly. The methods of firing steam boilers have simultaneously undergone radical changes, so that in addition to the lower investment cost, due to the decreased total capacity of steam raising plant required, there is the further investment gain due to the more intense utilization of the plant. In view of these considerations, there will be no difficulty in realizing that a given outlay for buildings and machinery will

*This is explained in my paper entitled "The Cost of Manufacturing Electricity", page 617 of the *General Electric Review* for September, 1913.

be adequate for delivering much more electricity per annum than formerly.

At the same time it must be recognized that in and near large cities there has been a counteracting tendency to require much finer buildings with much greater attention to architectural effect, and since, as Mr. Lieb has pointed out, the cost of land and buildings may easily be the largest item for such undertakings, any lower investment cost per kilowatt for machinery permits of a much less percentage decrease in the total cost than is obtained in the case of such plants as those to which my paper had specific reference. My paper dealt exclusively with plants of enormous capacity (in this case 100,000 kw.) located under such conditions that the outlay for machinery constitutes much the largest item. Under such circumstances the contrast between a modern plant equipped with machinery purchased at modern prices and the best plant which could be put down ten years ago and which would be of much smaller total capacity, owing to the then relatively small demand for electricity, is marked.

It should, in conclusion, again be emphasized strongly that my estimates do not apply to plants located in or near large cities. On the first page of my paper I called attention to "the great field for electricity for large manufacturing enterprises which can be located near the source of electricity supply." I expressly stated that my costs applied to the manufacture of electricity "in bulk" and "under favorable conditions" and I was very precise in pointing out that my costs did not apply to electricity manufactured in and near large cities.

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DISTRIBUTION OF ELECTRICAL ENERGY

REPORT OF SUB-COMMITTEE ON DISTRIBUTION

P. JUNKERSFELD, CHAIRMAN

IN THIS report your committee has submitted an outline of what it believes to be good engineering practise in the distribution of electrical energy for various purposes and under various conditions, which outline it is hoped will encourage and direct further attention to this vitally important matter.

The distribution of electrical energy in a given area, like the distribution of any raw or manufactured product, any commodity or utility, depends fundamentally upon the density or number of points of consumption or of use within the particular area. Other things being equal, any given method of distributing electrical energy should afford better results, reliability and economy, in the denser of two equal areas.

In practise, all other conditions, as well as areas, vary widely, because electrical energy is used for so many different purposes and in such rapidly increasing quantities. Electrical energy should be distributed in such form and at such voltage as will produce the best final result, all things considered, and each given proper weight. A full consideration of best final result immediately involves economic questions beyond the limits of this report, including the generation of electrical energy for practically every purpose by interconnected power houses under unified operation. The advantage of unified operation of power houses has, however, been thoroughly demonstrated and is quite generally recognized in this country and abroad. In all such cases most of the electrical energy required in a given area or community is usually generated in relatively large economical power houses and, to secure the best result in distribution, in such form as will best lend itself to meet the predominating demand in that community.

Such unified operation or centralized generation of electrical energy has so far usually been limited to power houses, and in

some cases includes the transmission to substations. In a few cases this centralization has recently been carried a step further to include the substation. In one of these cases, very large amounts of electrical energy had been supplied by the electric power company to each of two competing metropolitan railway systems, one elevated and the other operating on the street surface, both serving the same territory (the north and west sides of Chicago) and each operating its own substations independent of the other railway system. Supplementary contracts have recently been made under which the power company leased all of the substations of the elevated railway system and then contracted to exchange conversion service with the surface railway system. The power company also agreed, with necessary limitations, to build new substations where needed to deliver 600-volt direct-current energy to either of the above two systems.

As a result, the elevated railway system in this territory will be supplied very soon from 13 distributing substations instead of seven as formerly, and the surface railway system in this territory from 18 distributing substations instead of 10 as formerly. The average feeding distances are thus even at the start almost cut in half and make possible very large savings in distribution. Four of the additional substations are owned by the power company and will be also used for distribution of electrical energy to its general lighting and power customers, thus making a further saving in distribution investment and operating expense in that community.

In one of the cases above mentioned, a single substation with 4000-kw. synchronous converters supplies 600-volt direct current to three different railway systems, where under former methods three separate small substations would have been necessary. In another, direct current at 250 volts to a three-wire Edison system and at 600 volts to surface railway systems, is delivered from one substation instead of two. In both cases the investment in high-tension cables from the power house, in substation land, building and equipment, was about one-half what it would have been if the two or three separate substations had been built in each case. This reduction in investment results from: (1) less reserve high-tension cable; (2) less land and building for one large substation than for two or three small ones; (3) less cost per unit of substation equipment because of larger units; (4) less cost per unit of demand in kilo-

watts on one substation than on two or three, because of considerably lesser amount of spare capacity in kilowatts to give equally reliable service.

The operating expense for the one large substation was practically no more than the operating expenses for each of the two or three small ones, thus reducing these expenses one-third and one-half, respectively, in the two substations referred to.

In the above cases the high-tension supply to the substations was all at 25 cycles. Almost the same possibilities for economy exist in many cities where the general supply is at 60 cycles, as 60-cycle synchronous converters have now been developed to a point where in all except possibly the very largest units they are comparable with 25-cycle synchronous converters.

This tendency toward utilizing as many substations as possible for distributing all electrical energy (of whatever form or voltage) required within the economical radius of each substation, must result in large savings in future. Especially is this true when we realize that today only about one family out of four in this particular territory of rapidly growing population is enjoying the use of electric service. The possibilities in demand for electrical energy in transportation and industrial work in this particular territory seem equally promising.

The great importance of the subject of distribution of electrical energy is further indicated by the fact that in the average centralization system in a large city the fixed charges and operating expense of the distribution system are nearly three times the fixed charge and operating expense of the power house. This includes all equipment and conductors between power house switch gear and the customers' premises and refers to kilowatt-hours sold for general light and power, exclusive of bulk supply.

All expenditures of every kind for electrical energy for every purpose in any community should be viewed from the standpoint of such community, because that community in the end reaps most of the benefits, if any, and suffers most of the losses, if any, that result from the particular manner in which electrical energy is generated and distributed in such community. The advantage of centralization in generation of electrical energy is generally recognized, but the advantage of some centralization in transmission and in the substations is not so well understood.

In addition to the centralization of electric power generation, the centralization of distribution, at least the transmission to substations and the conversion therein, should always receive the most careful consideration.

The use of a single substation building for distributing electrical energy reliably and economically for general lighting and power, for surface railways and for elevated railway trains, has already been demonstrated. It is only a small step farther to distribute 600-volt direct current for steam railroad terminal operation from the same substation. If necessary, 1200-volt instead of 600-volt direct current could be distributed from the same substation and still effect a considerable saving if enough foresight and breadth of view is exercised by all parties interested.

Beyond the substation it is also very desirable to have centralization, at least to the extent of a single system for all general supply. The wastefulness of two different systems of mains for general supply overlapping in the same area, is quite generally appreciated. Different systems have, however, been well standardized for different conditions as, for instance, the Edison three-wire system for the denser portions or business districts of large cities, and the alternating system for practically all other general supply. In addition, there are various problems in distribution that are peculiar to the particular purpose for which the electrical energy is used.

In the following sections several of the most important problems in the distribution of electrical energy have been treated by members of the Committee who have had particular experience in these problems, which are as follows:

Three-wire d-c. distribution, by P. Torchio.

Alternating-current distribution, by H. B. Gear.

The relation of consumers' apparatus and wiring to distribution, by H. Goodwin.

D-c. distribution for surface lines, urban service, by R. H. Rice.

D-c. distribution for underground and elevated railways, by E. J. Blair.

D-c. distribution for interurban and steam railroads, by W. G. Carlton.

A-c. distribution for interurban and steam railroads, by W. S. Murray.

The relation of distribution problems and switching equipment, by E. B. Merriam.

Distribution for street lighting service, by P. M. Lincoln.

This report, including the sections and references therein to other contributions on the distribution of electrical energy, is supplemented by a list of references to such contributions from American and foreign authors as have been put into book form or have not been presented before the American Institute of Electrical Engineers. This list of references on the subject of distribution of electrical energy it is hoped will supplement to some extent the recently published Index to the TRANSACTIONS of the American Institute of Electrical Engineers—1884 to 1910 inclusive.

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APPENDIX I. THREE-WIRE D-C. DISTRIBUTION

BY PHILIP TORCHIO

The modern three-wire d-c. distributing systems consist essentially of a three-wire network of distributing mains fed by a multiplicity of cable feeders delivering current at different points of the network of mains, and a system of substations supplying the current to the feeders.

With the exception of the former low-tension d-c. generating stations, which have been replaced by the modern substations receiving high-tension alternating current and transforming it into low-tension direct current, the complete three-wire distributing network of over 25 years ago is still giving in every respect its full 100 per cent service alongside of all subsequent additions. This is almost a unique instance of permanency of usefulness of electrical apparatus used by central stations.

FEEDERS AND MAINS

The current was formerly distributed underground by Edison tube feeders, but in the last 15 or 20 years the cable system has superseded the former tube systems. For feeders, concentric cables with pressure wires are often used, they being either armored and laid in the ground, as is done mostly abroad, or being drawn into subway ducts, as in this country. In other cases single-conductor cables are used with pressure wires in the main cables or separate pressure wires outside. The network of mains consists of three single-conductor cables, of equal copper cross-section, drawn in distributing ducts in the

streets near the curb line or sometimes under the sidewalk. This system of mains is interconnected at each street crossing, thereby making a solid meshed system. Feeders, which are laid from the station to a number of suitable points, end at a junction box into which enter the feeder cable and pressure wires, and from which issue the main cables tying to the network of mains meeting at that intersection of the street. The junction box may be installed in the manhole or just outside in the street. The neutral main cables are spliced together and grounded at frequent places; in addition, there are neutral feeder cables starting from the substation and going to different points on the system with frequent grounds and taps to ramifications and to the neutral mains. The total amount of copper for neutral feeders is about one-twelfth of that for positive and negative feeders.

In a large system the amount of copper for feeders and mains in per cent of the total is as follows:

Feeders, positive and negative	58.9 per cent
Feeders, neutrals	4.8 " "
Mains, positive and negative	24.2 " "
Mains, neutrals	12.1 " "

Subway Ducts

Fig. 1 shows an arrangement of manhole, feeder junction box, trunk ducts and distributing ducts with a service handhole. Handholes are placed at convenient places along the distributing ducts and service connections are made to the adjoining buildings by tying service cables to the mains as indicated in the drawing.

These service cables are drawn in an iron or fiber pipe laid in the ground and ending in the basement or cellar of the building to be supplied.

Service Connections

At the customer's service the supplying company places a disconnecting switch and protective fuses and its current registering and metering devices.

Fig. 2 illustrates a type of modern service connection for lighting and power, consisting of specially designed porcelain blocks, which are equipped not only with fuses and all the connections to the watt-hour meters, but also with clips, by means of which the testing of the watt-hour meters on the customer's premises can be readily accomplished by inserting a plug with connections to the testing apparatus, thereby avoiding inter-

ference with the supply of current to the customer while the test is being made.

All of these appliances are enclosed under covers which are locked and sealed. From this point the customer derives his supply, three-wire for lighting and two-wire for power, which services are usually metered independently.

Standard Voltages

The usual distributing voltages used in this country are, $2 \times 110 = 220$ to $2 \times 120 = 240$ volts, though in a very few instances $2 \times 220 = 440$ to $2 \times 240 = 480$ volts are used.

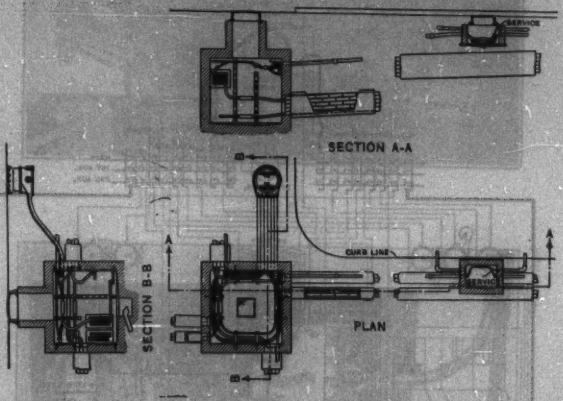

Fig. 1

If the multiple tungsten lamp eventually encroaches into the field of the arc lamp, the advantages of first cost and greater radius of the higher voltage systems would assume greater prominence than heretofore.

Substations

In general the full double voltage is generated by the converters or the motor-generator sets at the substation and the neutral of the system is secured by several means, among which are storage batteries, balancer sets, derived neutral from transformers, and other means.

Fig. 3 gives a diagram of the principal elements of a substation. The leads of the positive and negative connections are brought to separate boards. The neutral connections are made not at the board, but in the basement of the substation

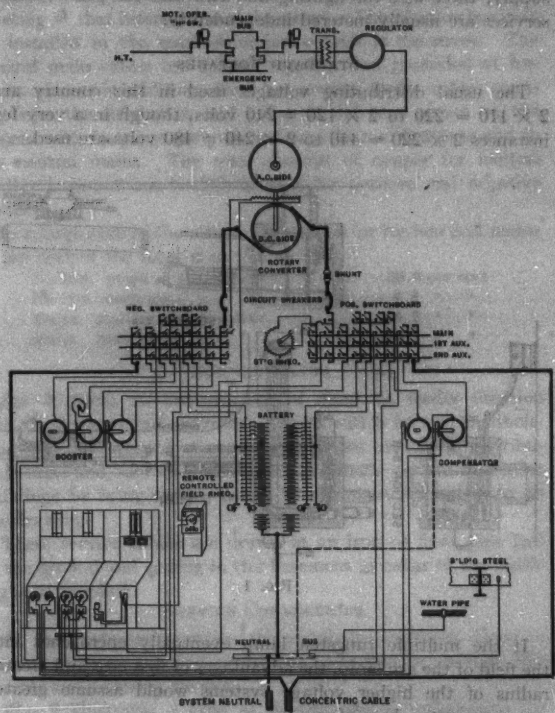

FIG. 3

or in the cable vault. Each of the two separate positive and negative d-c. boards is equipped with multiple buses, and all the feeder switches are selected to connect to any of these several buses. By this arrangement, according to the load requirements different machines can be operated on different buses at dif-

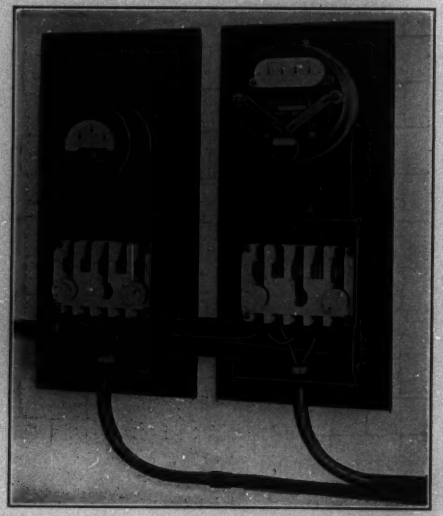

FIG. 2 [TORCHIO]

FIG. 4 [TORCHIO]

ferent voltages, and the shorter feeders can be connected to the low-voltage buses and the longer or more heavily loaded feeders to the higher voltage buses, thus securing voltage regulation throughout the network.

Fig. 4 illustrates the type of these selective switches used for converters and feeders, and the method of installation. By means of this edgewise system, the space occupied by the d-c. switches is reduced to a minimum, so that amounts of power as large as 30,000 kw. at 240 volts can be distributed from one substation.

The references give valuable material on the modern tendencies in substation design and equipment which cannot be treated fully in a brief review of this kind. We may mention, however, a few features of the latest developments which made possible large improvements in economy and simplicity of station. Among them stands foremost the development of the commutating-pole synchronous converter. This, in conjunction with graphite brushes with slotted commutators and self-lubricating copper graphite brushes for the collector rings, has made the operation of synchronous converters practically independent of attendance, except for the starting up and shutting down and the periodic cleaning and setting after the machines are shut down. Other important innovations have been the split-pole synchronous converter and the synchronous booster converter for obtaining regulation.

The manufacturers have produced units as large as 4000 kw. and they are now prepared to furnish still larger units if desired. Converters are usually six-phase and have been in many cases operated with double delta connection, though from recent tests it would appear that diametrically connected converters will operate practically under the same conditions as a double-delta-connected machine, and still have the advantage of greater simplicity of connections between transformers and converter. The synchronous converters are usually started from the d-c. end.

Air-blast transformers have been used most extensively and the practise of one large company is to have the blower motor connected directly to the secondaries of the transformers, so as to start it when the transformer is energized.

Storage Batteries

The installation of storage batteries at substations is a distinctive feature and great progress has been made in the last

few years in the adoption of the stand-by batteries, consisting of very thin plates, similar to those used for electric vehicles. These batteries can give for a short period of time large current discharges and often are designed to give, say for ten minutes, the full output of the substation in case of emergency.

Material improvements have been made in the method of end cell switch controls and connections.

Control

In very large systems great care is given to a number of such details, like the standard voltmeters for regulating purposes; the station lighting and power supply from duplicate sources; the telephone connections to the generating stations through independent lines and public telephone exchanges; and the emergency signals controlled from the generating station, giving simultaneous instructions by code to all the substations on the system.

APPENDIX II. ALTERNATING-CURRENT DISTRIBUTION

BY H. B. GEAR

The distribution of alternating current will be considered to include both *bulk supply* and *general distribution*. In the larger cities where the general distribution is made from substations, the bulk supply of energy is distributed by means of three-phase alternating current from the source of power to the points of distribution where it is converted to the form required for general purposes, for street lighting or for railway purposes. These lines are so numerous, and are so related to each other through tie lines, that they constitute a magnified form of distributing system with problems peculiar to themselves, which require consideration which might be lost sight of if they were classed as transmission lines.

Bulk distribution systems will be considered without regard to whether the energy is used for alternating-current distribution, direct-current distribution, or electric railway work, after its conversion.

Bulk Distribution

These systems are quite universally operated on the three-phase system at 25 or 60 cycles and at 6600 to 20,000 volts. The lower voltage is used where the radius does not exceed six miles (9.6 km.) and averages much less. In some systems the

longer lines have been raised to 20,000 volts or more, to handle the supply to suburban districts more flexibly. In the vicinity of Berlin there is an extensive 30,000-volt cable system serving the outlying parts of the city and suburbs. The German and English cable manufacturers have apparently been very successful in the production of cable for voltages above 20,000 volts, and such transmission lines are placed underground much more generally in Europe than in America.

The choice of frequency is fixed by the relative proportion of energy converted to direct current through synchronous converters. Where the direct-current load greatly predominates, 25 cycles is used and frequency changer sets furnish the alternating-current supply at 60 cycles. Where the alternating-current distribution predominates the power supply is often generated at 60 cycles. In several cases both 25 and 60-cycle generating systems are maintained, reserve capacity for each being secured through frequency changers.

Bulk supply systems have been developed in America chiefly on the principle of radial lines. A radial system is built up by the use of direct lines from power station to substation, one such line usually being sufficient to carry the load when the substation is established. The reserve source of supply, which is imperative, is usually secured by a tie line from another substation; or, in case of a small substation, by tapping another direct line at a convenient point. These conditions are illustrated in Fig. 5, which shows methods of supplying three substations of moderate size. In the three cases here shown it is assumed that the direct lines have a capacity of about 3000 kilowatts.

In cases *A* and *B* the failure of either direct line is provided for through the reserve tie lines. In case *B* a tap connection to one of the direct lines is used to save unwarranted cable investment. Either of the direct lines carries the entire load in conjunction with the tie lines in case of the failure of the other.

Case *C* shows the development of case *A* after the combined load of the three substations exceeds the capacity of a single line.

The ring system of case *A* may be used to take in any number of industrial power consumers up to the capacity of the cable; the substations in this case being on or very near the customer's premises.

The transmission system of one of the large companies in America has been developed on the principle of duplicate lines

arranged with substations in tandem. The converting units in each substation are divided into two sections so that an interruption on either line interferes with only one-half of the capacity in operation. These lines are protected by overload circuit breakers actuated by definite time-limit relays, so set that they will operate in tandem; that is, only that part of the service is interrupted which is beyond the fault in the cable.

As the loads increase and require more lines, the importance

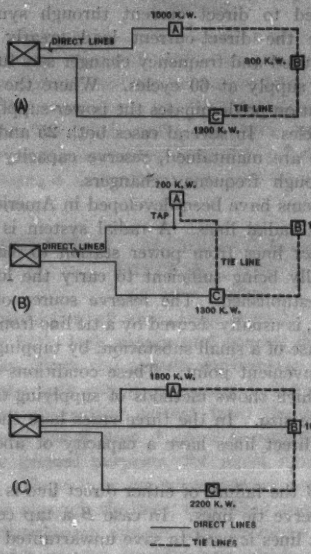

FIG. 5

of having a diversity of routes to guard against the failure of two or more cables to the same substation becomes apparent. This condition is illustrated in Fig. 6. The congestion near the power station must be guarded against by limiting the size of duct runs and providing several separate conduit routes.

As substation loads increase, the percentage of reserve investment becomes smaller, as one reserve line is sufficient for the three substations. Thus the reserve investment is about

one-eighth of the total in Fig. 6, whereas it is about forty per cent in Fig. 5.

It is usual to provide a transfer bus at substations so that any line can be connected to either tie line or to any converter.

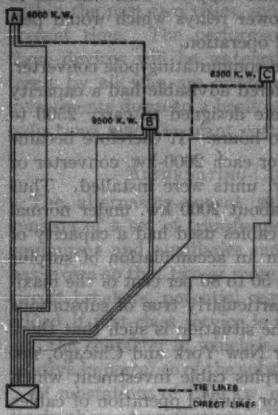

FIG. 6

A large proportion of the lines making up bulk supply systems in large cities is placed underground in lead-sheathed three-conductor cables drawn into ducts. The most economical use of capital is made when such cables are as large as can be properly handled. The kilowatt capacity of a high-tension cable at a given voltage increases more rapidly, with increasing sizes of copper, than the cost of the cable. The most economical cost per kilowatt, therefore, requires the use of as large a cable as it is practicable to draw into a standard duct.

The following table gives the maximum sizes of three-core cable which are installed at the present time and their approximate continuous capacity at various voltages:

Volts	Size of each core	Amperes	Kv-a.
6,600	350,000	290	3,200
9,000	350,000	290	4,500
13,200	250,000	220	5,000
20,000	150,000	145	5,000

The current values are taken for average conditions. They are somewhat high for situations where the facilities for heat radiation are poor, or where there is a considerable number of other cables liberating heat in the same duct line. These amounts of power could also be exceeded for a few hours during a peak load, without risk of injury.

Previous to the last two or three years it was not always

satisfactory to operate high-tension lines in parallel at the substation end, since a fault in either of the cables supplying a substation is likely to open the circuit breakers of cables not affected, thus shutting off the entire supply. This was due to the absence of reliable reverse-power relays which would permit the most satisfactory parallel operation.

Prior to the development of the commutating-pole converter, the largest unit which was considered advisable had a capacity of 2000 kw. These machines were designed to carry 2500 to 3000 kw., however, for about two hours. It therefore became common practise to have a line for each 2000-kw. converter or for two machines where 1000-kw. units were installed. Thus the average load per cable was about 2000 kw. under normal operating conditions, and as the cables used had a capacity of 3000 to 4500 kw., there has been an accumulation of surplus cable capacity amounting to from 50 to 80 per cent of the maximum substation load. This is particularly true of substations having loads above 4000 kw. The situation is such that there is, at the present time in Greater New York and Chicago, not far from $1,000,000 worth of surplus cable investment which could have been saved if means for parallel operation of cables and larger converting units had been available prior to 1910.

The introduction of converting units of 3000- to 4000-kw. capacity for direct-current work and three-phase transformers of almost any desired capacity for alternating-current distribution has done much to improve this condition in recent years. These units permit the use of cables at a point near their full safe carrying capacity and make possible large savings in future cable investment.

Another source of relief has appeared in the development of protective relays designed to permit lines to be operated in parallel. The Merz-Price system has had large and successful application in the north of England in a field where its value is greatest; that of the distribution of industrial power in blocks of 200 to 1000 kilowatts by means of a high-tension network. This system unfortunately involves the use of pilot wires which, not being included in existing cable systems, make its introduction more expensive and difficult than a system of reverse-power relays. (An interesting modification of the Merz-Price system, in which so-called "split conductors" render unnecessary the use of pilot wires, has been developed in England; but so recently that little definite experience is available.) How-

ever, it is probably the most reliable means at present known of guarding against interruption of service by cable faults.

Modified forms of reverse-power relays have been developed within the past two years, some of which are under trial at the present time. The performance and further development of these devices will be watched with the most sympathetic interest by all who are interested in getting high-tension cable investments down to a basis of economy comparable with other reductions made in plant costs in recent years.

Alternating-Current Substations

The alternating-current substation, in its simplest form, consists of a set of transformers with a minimum of switching equipment and auxiliaries mounted outdoors. After the load has grown so that two or more distributing feeders are necessary, circuit breakers, potential regulators and instruments must be added if first-class service is required. These require a building, the character of which is dependent upon the location and relative importance of the substation.

In substations of 1000 kw. or less it is usual to find oil-cooled single-phase transformers. With larger sizes, air- or water-cooled units are more economical. In three-phase systems three-phase units are often employed in sizes of about 750 kw. and upward. In two-phase systems which are operated in connection with three-phase transmission lines, single-phase transformers are selected for the Scott connection.

When the power supply is generated at 25 cycles the frequency-changing motor-generator becomes a factor. This usually involves synchronous motors and introduces exciters, starting compensator and necessary accessories in the way of switchboard equipment. Motors of frequency changers are usually wound for the transmission voltage to save transformer investment, where the transmission voltage is not above 15,000. Induction motors are used in some cases to secure greater stability at times of system disturbance.

The induction type regulator has largely superseded the transformer type. The superior results secured from automatically controlled regulators in the regulation of pressure have made them standard for important lighting service. The details of line drop compensators, contact-making voltmeters, and motor control have undergone a steady evolution in the right direction in recent years. The adjustment of springs and condition of

contacts, however, still require periodical inspection and checking of pressure at feeder ends. In Chicago it is found necessary with some 200 sets of equipment to check each of them at least once in three months by the installation of recording voltmeters for a few days at the feeder end.

The improvements in transformer design, by which weights and costs per kilowatt of capacity have been reduced, and the increasing requirements of good service, have made some striking changes in the cost of transformer substations. The transformers, which one ordinarily thinks of as the chief item, constitute less than one-third of the cost of a modern 5000-kw. substation, housed in a fireproof building and equipped with the required quota of oil switches, automatic regulators, duplicate buses, instrument and control panels, etc. The automatic regulators, feeder switches and distributing buses make up about half the total cost. A large part of the facilities of a modern substation is necessary for the safety of operating and construction men whose duties must be performed without accident to themselves, to the service or to the equipment.

General Distribution

The distribution of alternating current for general commercial purposes is accomplished in America almost universally by 2200-volt mains supplying step-down transformers located near groups of consumers whose premises are served by secondary mains at 110-220 volts. There are a few installations of low-tension alternating-current feeders on the Edison system at 110-220 volts in business districts, and some installations of 220-440-volt mains have been made where it was desired to avoid primary lines.

Lighting is quite generally served single-phase; while power service is given from two-phase or three-phase mains. Two-phase systems are in use chiefly where this method of distribution was established in the early period of development and is too extensive to warrant changing to the three-phase system. Three-phase systems are standard for all new installations where polyphase supply is desired for general power service.

Single-phase distribution is cheapest for lighting and small power mains at the load densities usually found outside of business districts, as the smallest size wire which should be used for mechanical strength is ample for ordinary loads. Three-phase, three-wire primary distribution is preferable in cities

where substation loads do not exceed 1000 to 2000 kw., but four-wire distribution is most economical for larger loads and the greater distances which usually go with them in the large cities. The four-wire system—being a 2300-4000-volt system—permits the supply of larger power users at outlying points more economically than by three-wire, 2300-volt systems.

The ability to regulate pressure independently on the different phases with greatly unbalanced loads makes possible the use of single-phase lighting distribution without sacrificing the advantage of three-phase transmission on the feeder.

The supply of power service in manufacturing districts is sometimes accomplished by the use of separate power feeders, the lighting being carried on other circuits. In other cases the light and power are combined. The use of separate power circuits tends to produce a duplicate distributing system and requires increased feeder capacity on account of the lower power factor, while with combined service the lighting tends to keep the power factor up. The diversity of demand between power and lighting loads also makes possible a considerable saving in feeder capacity where the lighting load in a given district is of the same order of magnitude as the power load.

Thus the policy of a combined feeder system is preferable from the standpoint of both feeder and main investment, in most cases.

With modern pressure regulating apparatus there are not many situations where the lighting service cannot be made what it should be, when power is served from the same primary mains.

The primary main system cannot be interconnected as the mains in a low-tension system, because it is impracticable to provide fuse protection in such a way that it will isolate a section of main which is in trouble without simultaneously blowing other fuses through which the energy is supplied. Thus the primary system loses the advantage of parallel feeding, and requires that the feeder end be located as nearly as possible at the electrical center of the district which it serves. The arrangement which gives the best distribution of pressure thus naturally takes the form of a center of distribution with radial mains. These centers of distribution should be chosen so that the drop on the primary main will average about 2 per cent from feeder end to transformers. This limit is not always commercially feasible in the case of lines to outlying districts where the load is not yet large enough to justify the cost of extending a feeder.

The usual form taken by single-phase circuits laid out in this manner is shown in Fig. 7.

In cases where a feeder follows a main thoroughfare along which most of the load is located, and the side branches are short, the tree system sometimes is used. This tends to give high pressure at the near end and low pressure at the far end but saves the cost of a "back feed" main.

In three-phase, four-wire systems a modified form of the

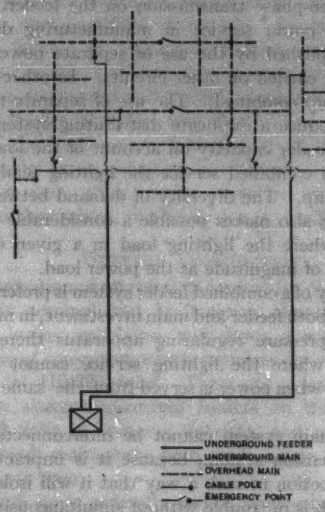

FIG. 7

center of distribution plan may be used, as shown in Fig. 8. The center of distribution of each phase is located with reference to the electrical center of the single-phase load carried by that phase. Since each phase can be regulated for pressure separately, this gives a good distribution in scattered districts, and permits feeders to be loaded more heavily than is possible when the load is distributed from a single center. In the denser business districts it is possible to pick up enough load for a feeder within a small radius, and a single center is adequate.

The separated centers of distribution can be used in two-phase systems but do not work out well for three-wire, three-phase circuits, since the line drop compensators cannot be set to take care of drop in the single-phase branch after it leaves the other phases.

Emergency Switching Points

Where portions of the primary system are underground and where mains of adjacent feeders come together it is important that suitable facilities be provided by which the mains of the two circuits may be joined together in emergencies. Cable

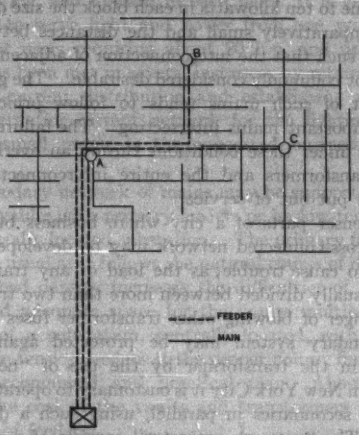

Fig. 8

repairs require a considerable time and if service is to be resumed promptly such emergency connections must be provided in sufficient number to permit the minimum interruption of service. Emergency switching points are also necessary as a means of putting sections of cable out of service while new cable taps are being cut in. The safety of linemen and continuity of service largely depend upon the facility with which sections of the primary main system may be controlled. Outdoor types of oil switches are used to some extent on important branches. The disconnecting type of porcelain pothead is found well adapted to this work, particularly at cable poles.

An arrangement of two adjacent feeders with mixed underground and overhead lines provided with facilities for emergency switching appears in Fig. 7. In case of the failure of any section of cable main, service may be resumed as soon as a repair man can open the potheads on the cable poles connected to that main, and close the emergency connection separating the overhead branches from the adjoining circuit.

Secondary Main Systems

The arrangement of secondary mains depends largely upon the density of the load. In outlying districts where the load runs from one to ten kilowatts in each block the size of secondary wires is comparatively small and the distances between transformers are such that the interconnection of adjacent secondary mains is not commonly considered desirable. The geographical arrangement of such mains tends to follow principal streets with few important mains intersecting. The failure of a transformer fuse under these conditions throws an overload on the adjacent transformers and the entire interconnected main is likely to be put out of service.

In the denser parts of a city where business buildings are served, a cross-connected network may be developed. This is less likely to cause trouble, as the load of any transformer in trouble is usually divided between more than two transformers, and the danger of blowing other transformer fuses is lessened.

The secondary system may be protected against trouble originating in the transformer by the use of "network protectors." In New York City it is customary to operate the larger transformer secondaries in parallel, using such a device quite generally. The "network protector" consists of a small transformer having the same ratio as the main transformer. The primary and secondary leads of the main transformer are carried through the protector in series. In case of a defect in the transformer the fuses of the protector quickly open the connections to the network and thus prevent the current from blowing the fuses of other transformers.

The interconnection of secondary mains has the advantage of permitting the use of spare capacity, where available, to take overloads on adjacent transformers. The diversity factor between different groups of customers may thus be utilized to make a reduction of transformer investment in some cases.

Motors cannot usually be served from lighting secondaries (except in the smaller sizes) without interfering with lighting service, on account of the fluctuations of pressure caused by starting currents. Where the requirements of lighting service are high it is therefore necessary to install separate transformers for power customers having motors of five h.p. and upward. In scattered residence districts it is often necessary to put motors of one h.p. and larger on separate transformers.

In alternating-current distribution in congested business districts where a network may be developed underground with loads of 75 kw. and upward in each block, it is very desirable to be able to serve light and power from one system except, perhaps, for users requiring about 20 h.p. and upward. The problem has been met in several instances by retaining the 500-volt direct-current distribution and establishing a three-wire Edison alternating-current network for the lighting and miscellaneous small power in the congested business portion of the city.

The secondary network of mains may be supported by transformers in vaults with primary feeders or by low-tension feeders from a centrally located substation. The primary feeder supply is the more usual as it follows the natural course of development.

As the load density increases the difficulties of getting ventilation and adequate space for the vaults multiply. The installation of a substation, centrally located, with alternating-current, low-tension feeders at the proper points, finally becomes the most economical and practical plan. About enough is saved in the cost of the vaults and transformers to offset the extra cost of feeders.

Where there is no direct-current power system provision must be made for alternating-current power service. In smaller cities this is provided for by separate transformers for the elevator service and for the larger general power. This permits the lighting to be served by single-phase, three-wire secondary mains.

In cities where lines are underground in the business district it is very desirable to be able to serve all customers from one set of mains as far as possible. This may be done by the use of four-wire, three-phase, 115-200-volt secondary mains supported by transformers and primary mains, or by low-tension feeders.

The proper distribution of lighting load between phases must

be maintained in order to avoid the effects of unbalance. The odd voltages of this system are a bar to its adoption if any considerable number of 220-volt motors is already in service, or if the lamps are rated lower than 110 to 112 volts.

When the load rises above 150 kw. per block, the problems of carrying large volumes of alternating current in lead-sheathed cables multiply, and a condition is reached where direct-current distribution seems to be a practical necessity from the cable standpoint, and the importance of the service requires the protection of the storage battery.

Transformer Selection

The determination of probable maximum demands of a user or group of users is of much importance in the selection of transformer sizes. Information based on experience and analysis of demands of different classes of users is necessary to avoid excessive investment in line transformers, as well as unnecessarily large core losses.

The systematic checking of transformer loads by the use of a suitable demand instrument is an important factor in keeping transformer investment within proper limits. This practise is followed by the larger central station companies quite generally. The practise of making contracts with large users on the basis of a demand measured by recording types of demand meters is of great assistance, as the maxima may be kept track of from month to month through the year and added load discovered as soon as it materially affects the demand.

The diversity factor in a group of consumers is so great in some cases that the demand of the group is very different from the demand of the individual users composing the group. The diversity factor is greater for residence consumers and similar classes whose use varies with their habits of living, than for commercial users whose requirements are fixed by more uniform conditions and whose demands individually are a larger proportion of their connected installation.

The following table represents average experience in the determination of demands of individual consumers and groups of consumers:

TABLE OF MAXIMUM DEMAND FACTORS

Classes of Users	Single	Group
Lighting Service		
Houses and Apartments	55 per cent.	20 per cent.
Offices	72 " "	60 " "
Small Stores	75 " "	60 " "
Hotels	35 " "	..
Churches	50 " "	..
Hospitals	60 " "	..
Manufacturing	70 " "	..
Power Service		
Less than 5 h.p.	86 " "	70 " "
6 to 10 h.p.	66 " "	62 " "
11 to 20 h.p.	65 " "	63 " "
Over 20 to 50 h.p.	53 " "	45 " "

The demand is given in this table as a percentage of the connected load.

Construction

The construction of alternating-current distributing lines for general service is very largely overhead. The use of underground work is necessarily limited to districts where the load density is such as to warrant the increased expense. In general, underground construction costs from three to five times as much as overhead work, where the load density is such as to require a 2200-volt main system.

Feeders and primary mains are sometimes placed underground on main thoroughfares, leaving the transformer secondaries and services overhead. This eliminates much of the risk incident to heavily loaded pole lines and avoids putting the more expensive part of the distribution underground.

The cost of distribution systems is materially increased by the necessity of doing the work piecemeal. The plant investment must be made with relation to the income which is likely to be derived within the period immediately following construction. The lines are therefore extended a block or two at a time, as the city grows, and the demand for service increases. The feeder system must be reinforced as may be necessary from time to time, to carry the added load. This involves re-arrangement of connections of primary mains and many complicated "cut-overs" which add to the expense very materially.

APPENDIX III. EFFECT OF CONSUMERS' APPARATUS AND WIRING ON DISTRIBUTION

BY H. GOODWIN

It is a comparatively simple matter to lay out a system of wiring a building, distribution lines and station apparatus which will give perfect service for any given combination of loads, but the duties of a distribution engineer are to make the best use of the lines available for supplying any proposed load without involving such cost as to make the proposition prohibitive from a commercial standpoint or without putting the consumer to such great expense for interior wiring as to make the service undesirable from his point of view.

When public electric service was first started it was for lighting purposes only. The service was generally only half night service; interruptions were frequent and voltage regulation was comparatively poor.

Conditions have changed and continuous good service has become in many cases a necessity.

Motor Service

The use of current for lighting was soon followed by the use of current for motors. These motors were at first small, and on account of the general irregularity of service no great trouble was caused by them. The power business has since become very important. The multitude of uses for small motors has also contributed very largely to obtaining many consumers for lighting. Since the introduction of electric current for power and lighting have gone hand in hand, it is natural that often a single service has been run for supplying both the light and the power and the consumers' wiring has been simplified as much as possible by the combination of lighting and power loads without regard to interference with service to one by the other.

Since motors cannot be started without a greater demand from the lines than is necessary to run them after starting, various well-known devices have been introduced to minimize the starting current.

Many electric power companies employ polyphase generation and both polyphase and single-phase distribution, the latter for lighting and small motors. In such cases it is necessary (in fairness to motor users as a whole and to the company) to have some fixed rule as to size of motor above which no single-phase service will be rendered and below which no polyphase

service will be rendered. This size varies from 1 h.p. to 7.5 h.p. with different companies, depending upon local conditions.

The polyphase motor means a lower initial and a lower maintenance cost for the user; and for the power company it means lower and better balanced starting currents and less interference with lighting service of other customers, but on the other hand polyphase motors mean greater line and transformer expense (except in large sizes) and greater metering expense. Such a rule as to maximum size of single-phase and minimum size of polyphase when once established in a community should be strictly adhered to, in order to save money both for the company and for the small polyphase motor user when he moves from one street to another.

In order to cut down the starting current the general practise is to require auto starters on single-phase motors from two h.p. up and on polyphase motors of five h.p. and up.

Many central stations are apparently satisfied to accept an installation with an automatic starter while others require that the starting device shall limit the current to a certain number of times the running current. Elevator and hoist motors are sometimes allowed a higher starting current than motors for general factory uses.

Recently automatic self-contained starting devices for motors have been marketed and have several obvious advantages and prevent unnecessary blowing of fuses.

The objections are that there is no adjustment by which the starting current can be reduced for classes of service where the starting torque may not be as heavy as the average and for which the motor must be designed in order that it may be adaptable to all purposes.

The general requirements for elevator motors are that they must be of the wound-rotor type. The device for cutting out the resistance is often mechanical and independent of the current drawn from the line instead of being directly dependent upon this current. It is very generally of a dash pot type which in use wears and works more and more easily, so that the motor is ultimately thrown across the line before it has reached speed at all.

In order properly to limit the starting current of an elevator motor cutting out the rotor resistance should be controlled by a device dependent upon the reduction of the current in the feed wires.

Summary of Motor Situation

In this motor situation it might appear that the manufacturer's point of view is diametrically opposed to that of the central station. The manufacturer can sell more motors if they can be made cheaper, but all the devices which the central station desires to protect its lines from occasional excessive currents cost much more. However, a broad view would indicate that the electrical art and industry will develop most rapidly and permanently by assisting in keeping as low as reasonably possible the rates for electricity, which cannot be done if central stations are put to excessive expense on account of the poor characteristics of the apparatus used by consumers.

Miscellaneous Apparatus

The question of allowing miscellaneous apparatus other than motors on lighting service still seems to be open and governed largely by local conditions. Rectifiers, cooking stoves, medical apparatus and the like are usually allowed on the lighting system, except where their use makes trouble. Wireless apparatus is generally classed as the most undesirable on account of the high frequency going back over the lines and burning out meters. It is generally required that this apparatus be supplied from a separate transformer.

Various electric welding and riveting machines are in use. Where the primary lines have a capacity of above 100 kw. these welders or riveters when used singly do not seem to cause much disturbance.

Consumers' Service Wiring

The effect of having to provide for the excessive current required for starting motors is that the consumer must wire, for all apparatus other than lighting and above ½ h.p., an independent service.

This service is connected to power mains which are standardized at 220 volts. This then makes it necessary to require that all motors of ½ h.p. and above be made 220-volt.

In places where practise has not advanced so far as to require a separate power main, it is also found well to require that all motors of ½ h.p. and over be made 220-volt, in order to minimize the starting current and its effect on the light.

Emergency Service

The necessity for emergency supply for industrial service is

a matter on which there is much diversity of opinion. In general, some emergency supply is justified when the load factor and demand are large enough to bring the investment and operating costs below the average. Unusual restrictions are placed upon services for fire pumps by the underwriters, based apparently upon an assumption that electric service is not dependable in an emergency. Continuity of service is now so well established that it would seem to be time for a readjustment of these rules.

Underground Service

The policy of introduction of underground service from underground lines by the central station company seems to be uniform. There is still, however, a divergence of opinion on the question of introduction of underground service from overhead lines. Some companies require lead-covered cable while others are satisfied with rubber-covered wire. However, the best practise would seem to be that the service be installed by the company. The expense must be borne by either party according to circumstances.

Relation of Consumers' Apparatus to Charges for Service

It is proposed to consider the effect of consumers' apparatus on the charges for service. Rates are often based upon a charge for kilowatt-hours with a minimum charge and discounts for greater use. This minimum is usually based on the rated horse power connected to the service or on demand measurement.

The use of the Wright demand meter makes it an advantage to the consumer to have apparatus of high power factor, since the meter registers maximum amperes.

There is on the market a motor which gives unity power factor and thereby improves the general power factor of the system. Where such a motor is available arrangements could be made which would either reward the consumer for buying apparatus of good power factor or penalize him for buying apparatus of poor power factor.

It would seem to be well if some system could be worked out for basing the minimum charge on the starting current of a motor instead of on the horse power rating.

If a system of charges could be instituted which would penalize the motor with heavy starting current or exempt in some degree the motor with small starting current it would appear to be a great advantage to both the central station and the customer.

Summary

Generating and substation service has now reached a very high plane of excellence. Small details of distribution tend to interfere with the regulation and service at the critical point where it is supplied to the consumer.

The solution is the placing of proper limitations on, and requiring the proper arrangement of, consumers' apparatus and wiring. There is a wide diversity of rules on this subject at the present time, but even the best leave something to be desired.

Therefore, let us look for improvement in these rules so that they may call for what is vital in this matter, which affects not only the procuring of new customers but the giving of good service to all.

APPENDIX IV. DIRECT-CURRENT DISTRIBUTION FOR SURFACE RAILWAYS—URBAN SERVICE

BY R. H. RICE

Electric railways very frequently have energy furnished to them over high-tension alternating-current transmission lines, and in this section of the report the substations are included in the distribution system. The component parts of the distribution system for urban street railway service are then:

1. The converting equipment in the substation;
2. The positive system from the substation switchboard to the car, including feeders and trolley wires;
3. The negative system, or returns, which complete the electric circuit from the car to the substation negative bus and include the electrical features of the track.

The usual city street railway system is characterized by having rather short feeding distances, large and rapidly fluctuating loads, and a wide variation in energy requirements at different hours of the day. Public demand is increasingly insistent upon quick and adequate service, better light and more heat, and this requires a greater amount of energy to be cared for in the distribution system, and greater reliability in its operation.

Substation Equipment

Substation equipment has become quite standardized and various installations differ chiefly in arrangement and in minor details. The equipment in a modern substation is housed in a well-lighted and ventilated building constructed for this purpose. It should be so arranged as to leave ample space for making repairs, and for installing or removing parts as may be necessary. A traveling crane is usually provided to facilitate such changes, but is now frequently omitted as the standard modern machinery is so reliable that it is rarely necessary to make replacements of parts requiring the use of a crane. Not only is there a saving in the investment for a crane but the building may be made lower and the side walls somewhat lighter, thus making an additional saving. Frequently no heating plant is installed, as the waste heat energy from the machines is sufficient to give a comfortable working temperature.

The supply of energy to a substation is almost universally from three-phase high-tension lines, and for railways is of 25 cycles. For city service such high-tension lines should be, and usually are, underground, to ensure more reliable service and to prevent danger to the public from exposure to high voltage. Conversion to direct current in the substations is by the universally accepted machine, the synchronous converter. It is desirable to have a separate high-tension line to serve each converter when the machines are of large capacity, and used in important city service. Switching arrangements are made to use any converter with any incoming line, so while the normal operation on the alternating-current side is by independent units of high-tension line, transformers, converters and other apparatus, emergency connections may be made as desired to interconnect the units. On the direct-current side the converters are operated in parallel, being connected to common positive and negative buses.

The synchronous converters used for railway purposes are 600-volt direct-current, compound-wound, and the later machines have commutating poles. Just a few years ago a 2000-kw. unit was the limit in size, but 4000-kw. machines are now in service. The cost of these large machines is less per kilowatt and they occupy but little more space in the substation, making the area per kilowatt much less than formerly. It is possible to place a 4000-kw. machine on the same foundations formerly occupied by a 2000-kw. unit. Care in design has

made this improvement possible, and the later machines contain numerous refinements in design which in the aggregate improve this class of machine very materially.

Switching is performed by motor- or solenoid-operated oil switches controlled from the main switchboard, and energized from a low-potential storage battery circuit. This battery circuit also provides current for the switchboard and station emergency lights.

An effort is made to keep the power factor of each station unit as near 100 per cent as possible. The rotary shunt field and the reactance are so adjusted that with a given high-tension line voltage and direct-current voltage the converters will operate with 100 per cent power factor when fully loaded. If the converters are operated under overload conditions there will then be a leading power factor, and if operated under less than full load there will be a lagging power factor. Most railway substations can operate very near to 100 per cent, and this is usually desirable when energy is purchased from a central station company. In some cases a penalty is attached, in the way of increased power cost, when the power factor deviates from 100 per cent.*

The Positive Feeder System

There is not much variation in practise among companies in positive feeder distribution. In general the trolley line is sectionalized by line breakers or section insulators, placed as desired, and each section is fed from a separate feeder panel in the substation. This feeder is very often composed of several cables running by different routes and tapping in at different points to a distributing cable running along the street, from which feed taps are made to the trolley wire. The above "radial" system of distribution is not so economical of copper as a "network" system in which all of the trolley wires form a continuous network and the feeders furnish energy to selected points of the network. As the load shifts from point to point all of the trolley wires and distributing cables act as equalizers and feed current to the point needed. It is difficult to locate trouble in an extensive network of this kind and also difficult to isolate the portion in which the trouble occurs, so that this method is not in common use. Some effort has been made to

*See "Power Factor Control by Rotary Converters," Nicholas Stahl, *Electric Journal*, December, 1913.

utilize the advantages of a network with the radial system by joining adjacent trolley sections through fuses or circuit breakers. Such a method has not been found satisfactory because it was impossible to adjust the connection so that it would distinguish between a heavy transfer of current from one section to another due to shift of load, which it should allow, and a heavy flow of current into a section due to short circuit, which it was not intended to permit. As a result these section connections usually became so unreliable that they could not be depended upon and were abandoned. A common practise at present is to provide knife switches, mounted in a pole box, which are normally open, but which may be closed on each end of a section if for any reason the feeders to this section become disabled. Such a plan provides a quickly operative and convenient device for ensuring continuity of service, as it is quite unlikely that the two sections adjacent to a disabled section would also be out of service.

The feeders may be underground or overhead. In the largest cities, and in many of the smaller ones, the municipalities require underground distribution at least in the central business district. The underground cables are installed in tile ducts and at frequent intervals lateral connections are made between these cables and the trolley wire overhead. A typical lateral connection consists of a tile duct, or fibre-lined iron pipe, running from a manhole to an adjacent trolley pole, and connecting with a vertical fibre-lined pipe clamped to the pole. This vertical pipe should be at least 10 ft. (3.04 m.) high, and just above its upper end a switch box and lightning arrester are attached to the pole by means of brackets. The lateral underground cable is run from the manhole to and up the pole and connected to the switch. Between the top of the pipe and the switch the cable should be stripped of its lead sheath, taped and painted with an insulating paint, and the top of the pipe should be capped with a split wood plug which is cored to fit the size of the cable used in the lateral. This should be done to keep snow and rain out of the pipe.

The lightning arrester is attached to the riser from the switch-box and the ground wire passes down through the pipe to a ground rod in the floor of the manhole, or is attached to the rail. The mode of grounding the lightning arrester is a disputed point to some extent, but undoubtedly a good connection to moist earth is preferable to grounding to the rail. Running

the ground wire through the lateral pipe may also cause some trouble, but this is frequently done, as no better method is usually available.

These laterals, although a relatively small part of the distribution system, may, if they are improperly insulated or installed, become the weak links which determine the strength of the whole distribution system. All cables should be rubber-insulated, the clamps holding the weatherproof riser to the pole should have an insulating band between them and the pole, and the cable should be held in the clamp by a split insulator. This gives three insulations between the conductor and the pole and will practically prevent "hot poles."

When the feeders are overhead the connection to the feed span is very simple, using either a jumper or making the span up with a tail. In this case lightning arresters are spaced along the line as local conditions demand, probably about five or six to the mile on an average.

The most commonly used trolley line construction is the standard span supported on tubular two- or three-section steel poles set at the curb line. The span wire almost universally used has been galvanized steel, but silicon bronze strand or copper-covered steel wire is now meeting with considerable favor. It has been found that steel strand frequently has very short life, especially in some manufacturing localities where atmospheric corrosion is especially pronounced, and other material resists such corrosion better than steel strand. The span should have two insulators cut into it between the trolley wire and the pole, and these, with some form of insulating hanger for the trolley wire, give three insulations from wire to ground. Clinch ears are to be preferred to soldered ears and are more frequently used. The tendency is toward simplicity in construction, but with such means as will increase safety and reliability.

Overhead trolley special work is an important item in construction. There are many complicated layouts at busy corners, and reliability of construction is paramount. Often with long cars it is necessary to set poles considerably back of the curb line to secure proper clearance on curves, and sometimes the city authorities require that poles be set back to the building line at important corners. It is desirable to develop standard layouts which are designed with a minimum amount of overhead material, and in which the stresses are so balanced as to secure reasonable assurance of permanence in the structure. In such

construction great care must be taken to align the trolley wire so that the trolley wheel can readily follow it without undue restraint.

In the 1913 report of the Power Distribution Committee of the American Electric Railway Engineering Association may be found specifications for material and construction of overhead trolley lines. In the various annual reports of the Board of Supervising Engineers of Chicago will be found the results of numerous tests on trolley material, such as poles and strain insulators, and also descriptions of special forms of construction. One of the most difficult things to secure is a good quality of trolley wire. High conductivity has been assumed as the chief criterion in securing a first quality wire and other desirable qualities have been sacrificed to secure this one. For a city system, with dense traffic, many feeders and frequent taps, the conductivity of the trolley wire is not of paramount importance. The qualities of toughness and high tensile strength are most important and it is desirable to place an upper limit on the conductivity and make the other requirements more severe than has usually been the case. The particular qualities required and the method of securing them in trolley wire is a subject worthy of considerable further study.

In any street railway system the load will fluctuate widely and it is a question of importance to determine upon what particular basis to design the feeder system. The load factor, that is, the ratio of the average load during the day to the maximum within the period, is usually from 40 to 50 per cent in an ordinary railway system. If the feeder system is designed to carry the peak loads without an overload on the cables, then during a large part of the day the current in the cables will be far below their safe carrying capacity and considerable copper will be idle. On the other hand, if the feeder system should be designed on a basis of say a six-hour average load, then the cables would be subjected to large overloads for a considerable period of time, heating would occur, the cables would more rapidly deteriorate, and a shorter life would result. The two-hour average is a good basis for feeder calculation, as the ordinary percentage of load in excess of this value is well within the overload capacity of the cable, especially since this excess load lasts for such a brief time. If this basis is assumed it means that the feeders will carry the entire load without being overloaded, except during two-hour morning and evening peaks.

The detailed method for computing the feeders necessary for a city system has been fully described by the writer in a paper published in the *Journal of the Western Society of Engineers* of June 1910, and in the Second Annual Report of the Board of Supervising Engineers, Chicago. Briefly, the method is to determine from the proposed operating schedules the total number of cars required during the "rush hours," and plot them upon a skeleton map of the system, thus making a "spot map." The afternoon maximum period is usually the heaviest service period, so that the car distribution for two hours of what is styled the "p. m. rush" is used on the map. On another map the trolley sections are indicated and the number of cars in each section determined from the spot map. This number of cars is then multiplied by the previously determined amperes per car, giving the current load for each section, which is placed at the center of load of that section. The required number of amperes per car should be determined in all cases by tests upon the particular equipment used and service demanded. This map is the "load distribution map" and shows very clearly the energy requirements of the system.

A study should then be made of the proper location of substations. The best probable locations and trolley sections for each station are selected and a graphical calculation of load center for each station is made by finding the combined center of gravity of the loads about each station. If the station locations chosen are not the most economical for distribution of copper, studies are made of comparative costs for other locations where the company may have property or where real estate may be obtained to advantage. After the station locations are definitely settled and shown upon this "station load center diagram" and the sections to be fed from each station are decided upon, light radial lines are drawn on the "load distribution map" from each station to the center of load of each section, which shows at a glance just what streets are fed from any given substation. Because of its appearance this modified "load distribution map" is known as the "spider diagram."

The most desirable routes for the cables are then determined, and the distance from the substation to the center of load of each section is measured on a large-scale map. After the computation of the cable necessary for each trolley section has been made a "feeder diagram" is prepared. This shows, by a properly selected code, from which substation each trolley section

is fed, the number, size and route of all cables, and whether the cable is underground or overhead.

The calculation of the size of feeders to serve any given trolley section depends upon four elements:

1. The load in amperes upon the section.
2. The distance of the section from the station.
3. The allowable drop in the feeders.
4. The current-carrying capacity of the cables.

It is desirable to limit the cables used to a few sizes only which may be kept in stock. The labor cost of replacing cables is practically independent of the size, and the larger sizes are thus more economical than the smaller. For underground cables the 1,000,000-circular mil size is a desirable maximum as it is readily installed in a standard 3 or 3½-in. (7.6 or 8.9-cm.) duct, in lengths convenient for handling. The current-carrying capacity of a cable does not increase as rapidly as its cross-section, because of the inability of the cable to radiate the heat developed. A great deal of study has been made upon the carrying capacity of cables, but no very definite knowledge has been obtained, or at least made public, upon the safe capacity of cables of various sizes and kinds in ducts constructed in ordinary street soil. A carefully conducted series of tests, having this end in view, would be very desirable. In overhead lines the maximum size of cables is determined almost entirely by the weight of cable it is convenient to pull over the cross-arms and to handle upon the poles. Probably the most common size in city service is 500,000 circular mils.

The allowable drop in a feeder may be of any value desired and it is not usually fixed at the most economical value. For a city system subjected to large peak loads a small drop, even at peak loads, is desirable even though it is not economical with respect to feeder investment, because it is important to operate the car motors at approximately their rated voltage, and the public requires good illumination in the cars, which cannot be secured with a fluctuating voltage. A value of 10 per cent positive line drop under peak load conditions is not too good a standard to set, as this means a 60-volt drop on the common 600-volt system. Even this is too large a drop to allow unless the negative return circuit is also designed for a small drop.

The load on the trolley section, and the route of the cables, have been determined as previously explained. It is only necessary to measure the feeding distance on a large-scale map and

then the elements of the computation are all known. The first step is to select the size of cable necessary to carry the load, and then compute the drop. In general for those sections near the substation the cable size fixed by current-carrying capacity is the proper size to use, but for the more distant sections the voltage drop limitation may require an increase in cable size. To make such calculations readily a chart may be used in which are curved lines of constant product, and superimposed upon these are radial lines showing the relation between distance and drop for various sizes of cables. Numerous other means have been devised for making the same calculations, but unless there is a great deal of computation to be done at one time special methods are not needed.

When a number of stations furnish energy to a city system, each station has a feeding district of its own and may operate independently of every other. But it is usually advisable to operate such stations in parallel so as to distribute the load and to have the benefit of assistance from other stations adjacent if any one is partially or wholly disabled.

Theoretically, the best manner of accomplishing this is to provide direct equalizing ties between the positive buses of the stations just as machines are equalized in a station. The objection to this is the large cost of the cable which is necessary, and which is not utilized directly in furnishing current to the cars. Essentially the same result may be accomplished by feeding a number of the more important trolley sections from two separate substations in such a way that in case of the shut-down of one station or of accident to one feeder, the cars on these sections could still be operated from the second station. These are designated as "tie-sections," and in addition to the above advantages, the feeders are so proportioned and calculated that on the whole system, in case of the shut-down of one or two stations, the cars on the more important sections can be operated from the remaining stations by interconnecting through these tie sections. The amount of energy drawn over these tie lines is regulated both by the relative resistance of the cables and by voltage control in the stations. This tie line system represents in a measure the factor of safety necessary for successful operation. The number of such lines varies with the importance of the stations and the density of traffic on the individual sections fed from them.

The Return System

The design of any overhead trolley system naturally involves provision for as direct a return of current as possible to the negative station busbar. Practically all city railway systems use grounded return circuits, the negative side of the distribution system being connected to ground. Although utilizing the full carrying capacity of the track rails insures that the greater part of the return current will follow this path, a certain proportion may reach other metallic underground structures which happen to offer another return path to the locality of the substations. It is very desirable to limit these "stray currents" to a small value in order to reduce the possibility of electrolytic damage to a minimum. Another decided advantage in making the return circuit very good is of course to reduce the energy losses. It is too often the case that the return circuits, except possibly for rail bonding, are almost wholly neglected, while the positive system is carefully planned and constructed. A poorly built negative system does not jeopardize life or cause delays to the same extent as similar neglect in the positive system would do, but elements of danger and loss are present which should under no circumstances be neglected. Negative feeders are unlike positives in that the cables form a network all connected to the tracks, instead of a group of independent cables running to unconnected portions of the trolley wires. The earliest form of return circuit was the rails only, which were bonded at the joints, and later a connection was made at the power station between the rails and the negative bus. As the loads and distances increased the drop became excessive on these simple track circuits, and supplementary conductors were provided to reduce the drops. The simplest method of doing this is to provide return conductors in parallel with the rails, and in such sizes as to reduce the return drop to the required amount. As approach is made to the substation the current increases, due to the accumulated load, and in order to keep the return circuit from being overloaded the supplementary conductors must be increased more and more the nearer the approach to the power station. The amount of such supplementary copper necessary is computed from the allowable maximum return drop.

It is difficult to make a calculation for this supplementary copper in the case of a city system whose tracks form a complicated network of conductors. But it can be done by assum-

ing the load distribution as in the positive feeder calculations and applying Kirchoff's laws to each element of the network formed by the intersecting tracks. The track lengths, conductivity, and loading being known, the drops may be found. If the drops must be reduced, this may be done by reinforcing the track circuits by additional copper.

In a grounded system, using the rails and supplementary copper for returns, in order to secure the full benefit of the supplementary copper it is necessary to connect the tracks frequently to this copper. This bond serves as an equalizer between tracks and enables the full track and cable conductivity to be utilized when the load is all on one track as well as when evenly distributed. The supplementary copper should be run through all special work and directly to the negative busbar. Where two cables cross, as at intersections, they should be electrically connected so that their equalizing effect may be realized. All rails on straight track should be at least well bonded, and preferably welded, so as to make the joint as good a conductor as the stock rail. At track special work, such as intersections, curves or crossovers, it is not usually feasible to weld at the rail joints, and the special work may thus be cut off from good electrical connection with the tangent track. To preserve the conductivity of the track circuit, special work cables are run through the special work and welded to the tangent track at each end. The value of the return circuit thus does not depend upon the special work rails, which may be removed without materially affecting the conductivity. Further details of such a system, and the results of tests on cable and bond terminals used as outlined above, may be found in the Third Annual Report of the Board of Supervising Engineers, Chicago, 1909.

The "insulated return system" is another method of constructing a railway return circuit. In this the return current is taken from the track circuit at various points, selected so as to maintain the track drop within any desired limits. The drop on the insulated cables may be of any amount up to the value which will cause the current to equal the carrying capacity of the cable, and the drop may or may not be of the same value on all the cables. The tendency will be for the shorter cables near the substation to become overloaded and sometimes a resistance must be inserted in these cables to limit the current and make the drop approximately equal to that on the other cables. It is possible to use negative boosters with these

insulated returns, but they add much to the operating difficulties, and have found no favor in this country. The insulated return system has been used much more extensively in European countries than here. Two papers* bearing especially upon this subject have been presented by Messrs. J. G. and R. G. Cunliffe and appear in the *Journal* of the Institution of Electrical Engineers.

Numerous matters of interest have not been touched upon in this report, but an attempt has been made to cover the fundamentals and to record good modern practise. Some important matters of design, such as the most economical number of substations, their location, and the maximum economical feeding distance, have not been discussed. Other matters of less theoretical character offer equal opportunities for investigation—such as the possibility of using higher voltage in operation, and the use of some form of three-wire system.

APPENDIX V. DIRECT-CURRENT DISTRIBUTION FOR UNDERGROUND AND ELEVATED RAILWAYS

BY E. J. BLAIR

The term "underground and elevated railways" used in the title of this report refers only to such railways when used for passenger service in large urban centers. The word subways may be substituted for "underground railways" to make the meaning more clear.

The railways of this description at present in operation or under construction in the United States distribute direct-current energy at approximately 600 volts bus pressure, using in general a third rail for the working positive conductor and the track rails reinforced by other conductors for the return circuit. Therefore this type will be given specific attention, although before passing to the details, mention will be made of other methods of distribution.

With the same type of distribution there is of course the possibility of increasing the potential. This would not seem desirable, thereby causing a departure from the established equipment standards, because for subways and elevated roads the density of loading will always be rather heavy on account of the class of service. This necessitates numerous distributing points, and on the other hand the length of feeding will

* "Electric Traction Vagabond Currents," Vol. 43, Part 197 (1909), and "Tramway Feeding Networks," Vol. 50, Part 219 (1913).

never be very long, so that 600 volts bus pressure can be accepted as good practise and the advantage of higher pressure would not offset the disadvantages. For the same reasons, no time will be spent in discussing the matter of alternating current.

Passing to other types of direct-current distribution, several modifications of a three-wire system are used in different parts of Europe. The most radical of these is the method used in the subway of the City and South London Railroad, which is a double-track tube using the third-rail conductors of the two tracks as the outside wires of the circuit and the running rail as the middle or neutral wire. This of course has the effect of minimizing the current flow in the track rail and thereby eliminating trouble from stray currents. However, such a method is only possible with a small and simple system, wherein the current loads are practically balanced between the two tracks. Another similar method is that used in the Nord-Sud subway in Paris, where a third rail is used for one side of the circuit and an overhead trolley wire for the other side with 1200 volts between the two and 600 volts from either to the track rail. This method would seem to be preferable to that of the City and South London, since it is not necessary to balance one track against the other. It also is used for the purpose of eliminating stray currents from the grounded track rail, by reducing the current in the track rail.

In London in most of the subways and tubes a fourth rail is used for the negative conductor, placed on the opposite side of the track from the third rail or more generally in the center of the track. This scheme of course entirely eliminates the difficulties from stray currents from a grounded track rail, since both sides of the circuit are insulated. It introduces operating difficulties due to the addition of the fourth rail, especially when one side of the circuit becomes grounded, as sometimes the results react upon equipment at distant parts of the line. It also adds to the burdens of maintenance, and complicates construction, especially at cross-overs and switches. Such a system is quite necessary in London on account of the severe limitations of return circuit drop imposed by the British Board of Trade when grounded conductors are used. With ordinary care the drop in track rail return circuits in the class of service under discussion may be kept within such bounds as will not cause electrolytic damage, and therefore to resort to

the fourth rail would not seem necessary unless municipal regulations exact it or unless for any given condition good engineering economy justifies it. However, in laying out a new system it would always be well to weigh carefully the merits and costs of the fourth rail system against the method of track rail return with its necessary auxiliary copper.

The type of construction common in the United States, namely the third rail with track rail return, is the particular object of study of this paper, since it is most common and more nearly meets all conditions. Where traffic is so dense as to require the construction of an expensive subway or elevated railroad, then the distribution must be laid out in such a way as to fulfill the following conditions, namely:

a. The maximum of reliability.

b. Ability to care for peak loads out of all proportion to mean requirements.

c. Heavy currents per train unit, and such close headway that extreme current densities obtain per mile of track.

In laying out such a system, therefore, the problems of size and amount of conductors, etc., are the least difficult for the engineer to solve, and the most important feature to be considered is that of simplicity and perfection of operation. The tendency has been to lay too much stress on the former and not enough on the latter. The methods of computation for feeder sizes, etc., described in that portion of the report given over to surface car systems, may be applied to some extent to calculations for elevated and subway work. In considering the operating features we find that the arrangement and division of the electrical distribution with respect to the track, or what is called sectionalizing, is worthy of the most careful attention.

An elevated or underground railway is, generally speaking, not composed of the complicated network of tracks and line distribution that is found on a surface car system in a large city. In other words, the current is distributed from substations or power stations in a straight line on both sides of the station, whereas for surface car systems the distribution radiates in all directions from substations. The fact that we have no networks to consider makes positive and negative distribution a much more simple task from the purely electrical engineering viewpoint, than is the case on surface roads. There seems to have been a tendency, however, to follow their precedents originally in methods of sectionalization, especially as to the

matter of connecting both tracks of a double-track road to the same electrical section. This scheme may have its advantages in economy of distribution, but its great disadvantages from an operating point of view more than outweigh such advantage. In effect it makes a single-track railway out of what should be a double-track road.

Investigation has been made of several properties, each having different methods of sectionalization and all of them fairly typical of conditions throughout the country. One of the methods is that described above, namely, both tracks being tied together. In another case a large part of the railroad is

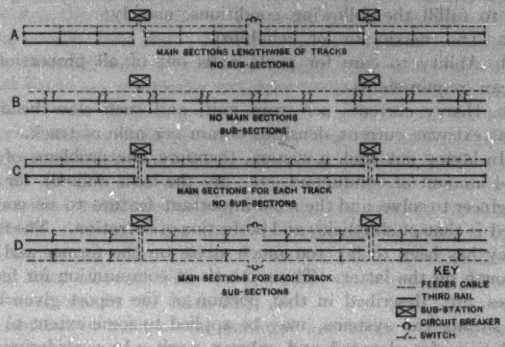

FIG. 9

connected on one common system of feeders, and switches every few thousand feet along the track are employed for isolating parts that are in trouble. This system is even more difficult to operate than the other. Still another system, and the best of the three, separates the two tracks from each other and also breaks the system up longitudinally at intervals. This latter system employs practically no track switches and therefore puts all section circuit breakers and switches on the switchboard in the power house or substation.

The diagrams shown in Fig. 9 typify these three systems of sectionalizing, with a fourth that is more nearly the ideal one. In each diagram a double-track road with no branches and with two substations is used to illustrate.

Fig. 9A is the system with the two tracks connected together on the same feeder cables and hence on the same circuit breaker or breakers in the substation. It is divided lengthwise at points opposite the substations and at a point half way between the two. At this latter location switches or circuit breakers are installed. Thus there are four sections shown. Of course in many instances there may be additional sections on the ends, with independent feeders. This system uses the conductivity to good advantage, but it is at once apparent that a short circuit of either momentary or prolonged duration on either track affects the other track and causes operation in both directions to cease.

Fig. 9B shows both substations feeding in on a common bus, that is, all feeder cables and conductor rails are connected in one general section. This also is very economical of copper, but usually necessitates several circuit breakers being in parallel on the distributing board, a condition which in itself is undesirable. To give an opportunity to isolate trouble, either track switches or track circuit breakers are installed at intervals of a few thousand feet. The track circuit breakers, to be effective quickly, both on opening and closing, should be controlled from the substation. In either event, whether they are remote-control or simple circuit breakers, a large amount of maintenance is entailed on account of the number involved, and the fact that they are not under the eye of an attendant. It has been found desirable on one road to eliminate the automatic circuit breakers and rely on switches only. Even with the circuit breakers, a heavy short circuit is apt to open the entire section at the substation. With such circuit breakers of the ordinary simple type it is also quite likely that one may open and leave its particular sub-section dead until such time as some one closes it, which usually involves a little delay. All things considered, it is felt that such a layout is even less desirable than that shown in Fig. 9A, since there is no sectionalization directly under the control of a skilled attendant, unless the remote control feature with its complications is resorted to.

In Fig. 9C the tracks are separated from one another and each track is sectionalized longitudinally, opposite the substation. Additional division may be had at as many points as may be desired along the track, necessitating additional feeder cables and panels. However, the substations will usually be sufficiently near together to do away with the necessity for this ad-

ditional division. It will be noted that the sections between the two substations are common to both or are "tie sections." This may be done either solidly or through switches or circuit breakers. This method is not as economical of copper as that of Fig. 9A or 9B, but is very satisfactory from an operating point of view. The only bad feature is the two substations feeding into the common sections, making it necessary to get both ends open in case of trouble. It has sometimes been found advisable, in order to secure better economy of distribution, to connect the two tracks together through equalizing circuit breakers. This, however, adds another complication when quick opening is desired. In general a system of this sort operates very satisfactorily.

Fig. 9D differs very little from the scheme shown in Fig. 9C and is the ideal to be worked toward. The "tie sections" are connected through circuit breakers, preferably remotely controlled by one of the substation operators, or, if at a location convenient to interlocking tower or dispatcher's office, by the attendant at such places. Sometimes the use of a circuit breaker with a no-voltage release is all that is necessary. It may seem that "tie sections" are not necessary, but in actual practise they are very desirable, since they permit of the shutting down of certain substations during very light load hours, and in addition they permit continuous operation of the road in case of accident to machinery in any one substation.

Such a system may be amplified by the addition of track switches or even circuit breakers where sub-sections are desired. It is believed, however, that good results will be obtained without either and that the switches without the circuit breakers will usually be all that is necessary. With the system shown in Fig. 9D in mind, it will be well to go into one or two general considerations. First, how big should such sections be? This of course will depend upon several factors, the first of which is the geographical layout of the railroad. This consideration has its effect on the location of substations and the consequent distance between them. Extremely large substations for elevated and subway work should be avoided and consequently this means numerous substations. This belief is founded more particularly on return circuit conditions than on positive conditions. For a substation feeding two tracks and in two directions only, it would seem undesirable to go much higher than 5000 kw. in capacity. Where the feed is in four or six directions,

as may readily occur at junction points, the capacity should not exceed 10,000 kw. This statement of course does not necessarily apply to what are called joint substations, where different classes of surface and elevated or subway loads are handled. Assuming a single line of double-track road served by 5000-kw. substations, it will readily be seen that in heavy elevated or subway service such stations will not be so far apart as to make "tie sections" very long. On the extreme ends of such systems single sections (not tie) should not be permitted to exceed two miles (3.2 km.) in length. This would mean a maximum of four miles (6.4 km.) for "tie sections." Of course with the usual elevated and subway service the sections would be of much less extent, if the size of substations were restricted to 5000 kw. The other restriction on the size of sections is, of course, that of load. Each section should be served by only one circuit breaker per switchboard to give the best results, and it is not desirable in railway service to run circuit breaker sizes much above 4000 amperes, and 3000 is better. The former size will permit of an overload setting of 8000 amperes, which should be ample for any one section.

To summarize, the single sections should be restricted in size to a mean load, during heavy periods, of 4000 amperes, and to a maximum length of two miles.

With sections limited as above, track switches or track circuit breakers would be necessary only when isolation of short pieces of track is required. In subways this feature adds somewhat to the factor of safety to the public, and is even further carried out by providing means so that any motorman or other employee can instantaneously cut off the power by pulling a nearby box or cord. Certain municipalities require sub-division into very short lengths in order fully to protect the public.

In dividing a railroad up into sections, due regard must be given to the point of separation of sections. In general the opening between two sections should not be closed by a car in passing over it. That is to say, one collector shoe must not be on one section while the other shoe is on the adjacent section. With certain types of equipment when trains are "bus-coupled" it is impossible to avoid this. Where gaps between sections are apt to be "bridged" or closed by a car or a train, it is quite essential to keep the voltage the same on either side of the gap. It is desirable so to locate the gaps between sections that they will occur at points where motormen are normally not draw-

ing power. A little care in the selection of gap points will materially improve operation of the car equipment. It is needless to say that from this point of view it is disirable to have as few gaps as possible. In sectionalizing, too much emphasis cannot be placed on simplicity in the switching arrangements, since this makes for speed in handling emergencies.

Complicated track junctions can best be handled as individual sections from the substation. There is always a tower at such places which affords an opportunity to further subdivide the junction through circuit breakers, so that in case of trouble at any given point, the towerman can immediately isolate it. This is of course carrying out the track switch idea to a certain extent.

Construction Methods and Materials

Briefly stated, it is not good practise to use third-rail conductors that are too light in weight, since they are much more difficult to maintain in substantial fashion. Further, it is not good to have third rails that are not reinforced by auxiliary copper. There is a temptation to run up the weight and conductivity of the third rail and not add the copper on certain outlying sections. In such cases, where breaks in the bonds around third-rail joints occur, it will be seen that without the copper to carry the current, a part of a section may become absolutely dead. So that, even if for regulation no auxiliary copper is required, it is a good thing from the emergency side, and even a small copper conductor will be worth while to insure reliability. If such a thing is not used an emergency switch to cut in and obtain a back feed from another section is many times quite worth while.

One of the distinct advantages to be obtained from a system such as Fig. 9c which does not use track switches is, that all the conductivity of the third rail is brought into play as part of the feeder system.

Substation construction for elevated and subway service is almost identical with that for city surface car lines. This has been covered in that part of the report dealing with the latter type of railways.

Return Circuits

This subject is such an important one that it hardly seems advisable to attempt to treat it as part of a general paper on distribution. Furthermore, it seems probable that more definite conclusions on the subject will be arrived at, shortly, than

have been existent before, on account of the combined efforts of the various engineering associations. Suffice it to say that with grounded conductors such as are used in most of the present systems, great care must be used to keep within proper bounds the potential differences along such conductors. This is what makes it essential to resort to small and numerous substations. In most cases it is not necessary to insulate the negative conductors, but with grounded conductors one good way to limit the drop is by the use of insulated negative feeders. Such an installation has a more direct application and is more necessary in subway work than on elevated lines. Certain it is that not enough attention has been paid to the negative circuit in past installations.

APPENDIX VI. DIRECT-CURRENT DISTRIBUTION FOR INTERURBAN AND STEAM RAILROADS

BY W. G. CARLTON

Prior to 1906, practically all direct-current operation on interurban or steam railroads in the United States was at potentials of approximately 600 volts. In general, power was distributed through an ordinary overhead trolley wire, this being reinforced by such additional feeders as were necessary. In a few cases power was distributed through third rails, the arrangement of third rail being practically the same as used on elevated and subway lines in the large cities. There was no electric operation of heavy trains on any of the steam railroads with the exception of the Baltimore & Ohio Railroad, at Baltimore, which operated trains through a tunnel at slow speed and for a short distance.

In 1906 the New York Central & Hudson River Railroad and the Long Island Railroad began changing over from steam to electric service in and near New York City. The Pennsylvania Railroad began electric operation through its tunnels in New York City in 1910 and about the same time the Michigan Central Railroad began electric operation through its Detroit River Tunnel. In all of these cases power was distributed over third rails at approximately 650 volts.

The New York Central and Michigan Central Railroads used a suspended type of third rail, contact being made on the bottom, the rail weighing 70 lb. per yard. (28.5 kg. per m.). The Long Island Railroad used a top contact third rail, weighing 100 lb. per yard. (40.8 kg. per m.). The Pennsylvania

Railroad also used a top contact third rail, but weighing 150 lb. per yard (61.2 kg. per m.). Where necessary, additional feeders were used to reinforce the third rail, and in some cases remote-control switching stations were installed for the purpose of connecting parallel third rails and cables and still being able to disconnect them quickly in case of trouble. With the roads mentioned, power was distributed from substations located from four to eight miles apart.

Railroads using the third-rail method of distribution have found it necessary for locomotive service to install a small amount of overhead third rail or trolley wire over long crossovers. This overhead conductor is not necessary where trains of motor cars are used, as they will span the gaps in third rails at crossovers.

The substation equipment for 600-volt service has not changed materially for several years, with the exception of the introduction of commutating-pole synchronous converters and generators and the use of larger machines. Storage batteries are not being installed to any great extent, and for protection against interruption to service, ample capacity in substation apparatus and in high-tension lines between generating stations and substations is relied upon.

It is not probable that potentials as low as 600 volts will be used for electrification of steam railroads, with the possible exception of those in and near large cities. At the present time the tendency is towards the use of 1200 volts or higher, not only for steam railroads but for interurban roads of considerable length. There are in the United States, 28 railroads operating or preparing to operate at 1200 volts or higher, the maximum voltage being 2400. For all of these roads, the distribution is by means of an overhead trolley, although one of them is using third rail for a portion of its work and a second road is preparing to do so. In general, the catenary type of trolley construction is used.

Power for operation at 1200 volts is furnished direct from steam-driven generators in a few cases, but as a rule is furnished from synchronous converters or motor-generators, these being either 1200-volt machines or two 600-volt machines in series. The only direct-current 2400-volt road in operation at the present time uses motor-generators with two 1200-volt machines in series.

The Butte and Anaconda Railroad installation is an example

of what can be done in handling steam railroad service. Direct current at 2400 volts is used. The trolley wire is No. 4/0 and but two feeders are needed, a 1,000,000-cir. mil for the positive side and a No. 4/0 for the negative side of the circuit. There are two substations 26 miles (41.8 km.) apart. In one direction trailing loads of 3400 tons are hauled, the maximum grade being 0.3 per cent. In the other direction trailing loads of 1000 tons are hauled, the maximum grade being 1.0 per cent.

The general problems of d-c. distribution for interurban and steam railway purposes are here omitted because, except for the weight of train units and consequent details of construction, they are not essentially different from those discussed by Messrs. Gear, Torchio, Rice and Blair, respectively, in earlier appendixes of this report.

APPENDIX VII. A-C. DISTRIBUTION FOR INTERURBAN AND STEAM RAILROADS

BY W. S. MURRAY

In a number of instances attempts have been made to connect cities using direct current on their overhead systems by interurban lines using alternating current on their overhead systems. This necessitated great complexity in the design and control of the motive power equipment to perform the duplex operation. The attempt naturally did not meet with success, as it was clearly an abuse of the application of alternating current. It may, therefore, be said:

That the alternating-current contact wire in general has no application in the interurban field where the equipment must be common to city and interurban operation.

Economies in steam railroad electrification may be looked for and secured by providing a high over-all efficiency from the terminal of the primary transmission system to the drawbars of the trains. Such a system is the one delivering high-voltage alternating current from a single overhead wire, which while doing this also possesses the greatest adaptability and elasticity under the onerous conditions imposed upon it by modern heavy transportation.

By reason of the general acceptance and standardization of 25 cycles, such a frequency in a single high-voltage contact wire, while conforming to a periodicity generally in use, also permits all classes of equipment to operate beneath it, such,

for instance, as single-phase, split-phase, and, through the medium of a rectifier, direct-current motive power apparatus. Therefore, in the case of steam railroad electrifications, in virtue of the above-mentioned facts, it would seem reasonable to offer as recommended practise the use of a single overhead wire furnishing high-voltage alternating current of 25 cycles as the contact system for the motive power apparatus operated thereunder.

APPENDIX VIII. THE RELATION OF DISTRIBUTION PROBLEMS AND SWITCHING APPARATUS

BY E. B. MERRIAM

The principal problems in the distribution of electric power which are affected by switching and auxiliary apparatus may be classified as follows:

1. Maintenance of continuous service supply.
2. Protection against service interruptions due to faults in the distributing system and receiving apparatus.
3. Safe interruption of circuits abnormally loaded.
4. "Safety first" protection for all who come near the distribution system.
5. Operation of the distribution system at maximum efficiency.

Service Maintenance

The maintenance of continuous service supply is usually accomplished by feeding the distribution system from one of several sources of power supply through two or more buses or their equivalent. Connection is ordinarily made between the different parts of such a system by some form of switch in addition to a circuit-interrupting device.

For 250-volt three-wire Edison direct-current systems the switches are usually single-pole, single-throw, edgewise type. They are designed to be arranged in very compact form and economize space so that a large number of feeders may be controlled from a minimum size switchboard. For alternating-current and direct-current switching service at pressures up to 750 volts, it is customary to use the so-called knife blade or lever switch, mounted preferably upon slate and equipped with or without quick break features.

Alternating-current systems operating at pressures above 750 volts are equipped with plain lever switches furnished with detachable handles and usually some form of locking device for

retaining the blade in the closed position against the action of large magnetic forces which are often developed during short-circuit conditions. Up to 2500 volts, these switches may be mounted on marble bases, but above this pressure the best practise demands that the switches be mounted on porcelain insulators secured to iron or steel bases, and located remote from the switchboard.

For direct-current systems above 750 volts, remotely controlled lever switches are becoming standardized. These are usually mounted on porcelain bushings set in slate bases forming part of the switchboard panels.

In some cases, particularly in isolated plants, automatic devices are sometimes installed to connect the house service system with the central station distribution system in case of failure of the isolated plant supply, but such devices have only a limited application.

Service Protection

A means of giving complete protection against service interruptions due to faults which develop in the distribution system and receiving apparatus is now being diligently sought by manufacturers and operators. Their investigations have resulted in the development of numerous schemes for indicating the appearance of faults in the distribution system and for disconnecting faulty feeders without disturbing the healthy ones.

One of the indicating schemes depends for its operation on the unbalancing of the currents in the legs of a three-phase feeder caused by a ground or other fault. The unbalancing induces currents in special series transformers connected to the feeder and gives a visual and audible indication of trouble by tripping a shutter covering the number of the faulty feeder and ringing a bell.

Another scheme, originally developed abroad as a result of suggestions by Kallman and Andrews, depends for its operation on a difference appearing between the current entering at the supply end of the feeder and that leaving it at the receiving end when a fault develops. Until recently, it had not been considered for use in the United States because it requires the use of auxiliary wires to connect the devices placed at the ends of the feeders, and in some designs, special current transformers which may be balanced one against the other. Besides, under

some conditions, it gives no indication of failure of continuity of the auxiliary circuit, which thus renders the protective feature inoperative. It is very sensitive, however, and discriminates accurately between healthy and faulty feeders. It can also be so adjusted that it will disconnect a faulty feeder before the fault gives rise to dangerous circuit conditions.

A modification of the above, which eliminates the auxiliary wires, has recently been developed. This divides each feeder into two parts, placing the parts in the same or in separate cables. The incoming and outgoing currents at the ends of the two parts of the feeder are then balanced through series transformers connected to them, and the secondary circuit arranged as before.

A number of other schemes have been proposed and are in operation, which depend on various kinds of overload, reverse-power and kindred types of relays. The overload relays are usually made partially selective by some form of time delay whose value is in whole or part a function of the overload current. Three principal types of time delay schemes are now available. One depends on the retardation effected by an electrically driven gear train, the electric feature being actuated by the overload current. Another depends for its time delay on the action of a permanent magnet on a disk of conducting material rotated between its poles. A third depends upon the retardation effected by the expulsion of air from a bellows through a fixed orifice.

The reverse-power relays depend primarily on a reversal in the direction of power flow. Numerous forms have been developed in which the solenoid, dynamometer, and induction principles have been employed with more or less success. They all depend on the interaction between current and pressure coils and their range is usually limited by the high minimum pressure at which they will operate without requiring excessive current flow.

Circuit Interrupters

The safe interruption of circuits abnormally loaded presents one of the most difficult problems encountered in distribution.

For direct-current circuits up to and including 1200 volts the carbon-break circuit breaker is applied almost universally with eminent success. Above 1200 volts, however, it has been found necessary to adopt some form of magnetic blowout,

and reliable circuit breakers utilizing this principle have been developed for direct-current circuits up to 5000 volts.

For all alternating-current circuits, with but few exceptions, the oil-immersed circuit breaker is now considered standard. It has been the object of considerable study and research, with the result that its operating characteristics have been markedly improved. The design of contacts, characteristics and quality of the oil, and shape, ventilation and fastenings of the oil vessel have been given especial attention. Further improvements may be looked for in the direction of increased speed of break, better confinement of the oil in the neighborhood of the arc, and an increase in the number of breaks in series per phase.

The duty demanded of oil circuit breakers has, however, been very rapidly increased of late due to the huge generating capacities now being concentrated in single units, and grouped in central stations. The stored energy of such systems has now become so great that it is no longer possible for the oil circuit breaker to dissipate it unaided. Various schemes have therefore been proposed and adopted for assisting in the dissipation of this energy. The first one places reactance in the generator or feeder circuits so as to limit the power which could be obtained on short circuit. This reduces the drain on the generating equipment and in turn reduces the effect of the abnormal disturbance on feeders other than the faulty one. Another scheme introduces reactance into the circuit to be interrupted after the abnormal disturbance has been manifested and before the oil circuit breaker clears the circuit. This scheme reduces the current that the oil circuit breaker must interrupt but does not limit the initial drain on the generating system or protect feeders adjacent to the faulty one. A third scheme introduces resistance into the circuit in shunt with the oil circuit breaker during its operation. This scheme is the only one which increases the energy-dissipating capacity of the modified circuit breaker and appears to represent the most efficient solution of the problem.

Safety First

The protection of attendants and others from injury caused by contact or otherwise with distribution systems is being daily given more attention. To meet this situation, manufacturers have placed on the market lines of so-called "safety

first" apparatus. It has all of the live parts enclosed in iron or steel compartments to which entry is prevented, except when the circuits leading in have been disconnected from the distribution system. These lines include all forms of switching devices from low-pressure, small-capacity, single-pole, single-throw, fused lever switches to complete switchboards, for use on 15,000-volt high-capacity circuits.

Operation Efficiency

The operation of distribution systems at a maximum efficiency requires a minimum investment in feeders and depends for its accomplishment, among other things, on the ability of the various switching and auxiliary devices properly to perform their functions. These devices, together with their limitations, have been discussed elsewhere in this report and repetition here is deemed unnecessary.

Conclusions

It is seen, therefore, that a considerable number of important distribution problems depend for their solution on the characteristics and performance of switching and auxiliary apparatus, and that strenuous efforts are being made to improve the various devices so that they will satisfactorily perform all their functions.

APPENDIX IX. DISTRIBUTION FOR STREET LIGHTING SERVICE

BY PAUL M. LINCOLN

The problem of distributing power for the specific service of street lighting is quite different from that of power distribution for commercial lighting and other purposes. There are two peculiarities which differentiate it particularly from the usual distribution problem. These are:

1. That the area over which the power for street lighting must be distributed, must, at the same time, be served by an entirely separate general distributing system.

2. That all of the power for street lighting service must be switched at certain predetermined periods of the day, being needed only in the hours of darkness.

The fact that street lighting is required only at night makes it desirable that this particular service shall be fed by a separate distributing system, so that the power for use thereon may be turned on and off at will from a single point.

The alternative to the separate street lighting distributing

system is to use the same distributing system for street lighting as for other purposes and to have the street lamps switched off and on singly or in groups at a point near the location of the lamps. This latter alternative presents so many difficulties that it has been used only to a very limited extent, where groups of lamps are located in a small area such as a small park or playground. Where lines are all underground it is usually cheaper to give this service from the general network and switch it at various points by hand than to build separate circuits.

The requirement for the simultaneous lighting and extinguishing of all street lamps led to the development and continued use of the so-called "series system." In this system, all of the lamps of a given circuit are operated in series at a constant current. The amount of current used varies with the type of lamp, from a minimum of about four amperes, with some of the more recent types of lamps, to a maximum of approximately ten amperes, which was the standard when Brush brought out his first arc lamps. Ten-ampere series circuits are also the standard current rating for long-burning flame carbon arc lamps, which have recently been developed and are being extensively used in this country. Approximately 20,000 of these lamps have recently been placed in operation in Chicago. The voltage on a circuit varies, of course, with the number of lamps, reaching a maximum of 10,000 to 12,000 volts in some cases. There are, at present in use, two methods of securing the constant current required by series street lighting systems:

1. The use of a constant-current generator, in which the voltage varies with the load on the circuit.

2. The use of a constant-current transformer, which receives constant-potential alternating-current energy and delivers constant-current alternating-current energy, the potential of which depends upon the load of the circuit.

The constant-current generator may be either direct-current or alternating-current, but practically all arc machines are of direct-current type. It is noticeable, also, that practically the only type of direct-current arc machine that has survived is the so-called "Brush arc machine," which is a direct descendant of the original machine designed by Charles F. Brush back in the days between 1875 and 1880.

The ease of securing constant alternating current by means of the constant-current transformer, together with the general

adoption of constant-potential alternating-current systems for general power supply purposes, has made the use of a-c. constant-current arc service very general. The invention some ten years ago of the mercury arc rectifier has also enabled us to obtain constant direct current from the constant-current transformers, using, as a source of supply, the standard constant-potential alternating-current systems that have now become standard. Therefore, the use of such constant-current transformers in conjunction with rectifiers has largely taken the place of the constant-current direct-current arc machines, and, as time goes on, the displacement of the arc machine by the rectifier will probably become more and more complete.

The advantages of constant-current operation, as compared to constant-potential for the operation of street lights, are numerous. They are so sweeping as practically to eliminate the constant-potential service for this purpose. They may be enumerated as follows:

1. The lamps may be lighted and extinguished from the central station exactly on any predetermined schedule. This is the fundamental requirement that has made necessary the development of a special distributing system for this purpose.

2. Constant-current circuits, as developed at present, have a relatively small ampere capacity (from four to ten amperes) and are available at a relatively high voltage (8000 to 10,000). Consequently, the investment in copper for distribution purposes is reduced to a minimum.

3. The constant-current arc lamp system is inherently stable, whereas the constant-potential arc lamp must induce its stability by means of a series resistance of considerable value. The amount of this series resistance is comparatively large in constant-potential circuits, since it is necessary to operate the arc on available commercial voltages which are higher than required. Naturally, therefore, this excessive resistance decreases the efficiency of the constant-potential arc lamp.

4. When metallic filament lamps are used instead of arc lamps on constant current, we also have important advantages. The filaments of the constant-current lamps are of larger diameter and shorter than those demanded by constant-potential lamps, and, as a consequence, the lamp is not only stronger and less liable to damage but also it is subject to smaller radiation losses on account of the smaller area exposed. This latter advantage is particularly noticeable in the "nitrogen-filled"

lamp which holds out so great promise of future developments.

A system of street lighting which is a compromise between the constant-potential system for individual lamps and the constant-current system is one in which a series of lamps is operated across a constant-potential circuit. In this system 2200 or other available voltage is used to operate a series of metallic filament lamps, each series having a sufficient number of lamps to make the total voltage across the series the same as that of the line.

In order to prevent the breakage of a single lamp interrupting service on the entire series, each lamp is shunted by a special reactance coil. This coil is so designed that it takes but a small proportion of the total current of the system while the lamp is burning. If, however, the lamp filament should break, the entire current of the circuit passes through the reactance coil without danger to the coil. This characteristic is obtained by designing the iron circuit of the reactance coil so that it is operated above the bend of the saturation curve when passing the entire current of the circuit. At the same time, it is possible to obtain a curve of regulation, so that a considerable percentage of the total number of lamps on the circuit may be out of service before the current on the whole circuit is reduced beyond allowable limits. In this system we may see a return to a system which was used at least twenty years ago. The writer well recalls the use of these identical devices in the apparatus that was built in 1892.

This system has the material advantage that it does not require switching service for each individual lamp, but that this service may be accomplished at one point for an entire series of 30 to 35 lamps. Also, it is quite possible to group the switches for a number of circuits at one point. By this means, therefore, the cost of switching may be reduced vastly below what would be necessary if each individual lamp required this service.

DISCUSSION ON SUB-COMMITTEE REPORT ON "DISTRIBUTION OF ELECTRICAL ENERGY" (JUNKERSFELD, ETC.), NEW YORK, FEBRUARY 27, 1914.

H. L. Wallau: The keynote of Mr. Junkersfeld's paper is "centralization." Lack of centralization means a partial or total duplication of land, buildings, equipment and labor. In the proportion that centralization is accomplished, duplication is eliminated and further advantages accrue: (1) increase in the capacity connected that may be served from given equipment, due to increased diversity; (2) reduced investment per kilowatt, due to the use of equipment of larger unit size, and (3) reduced operating expenses.

These benefits lower cost, and as a direct consequence, rates are reduced; and generally they also result in greater reliability of service. A reduction in rates is always followed by a healthy growth in load, and increased reliability of service means much in permanently holding customers.

Other things being equal, one kind of current at one voltage supplied to all consumers would make for minimum cost. This consummation, however devoutly to be wished for, will probably never be realized, as each kind of current supply furnished has a field of usefulness of its own. Improvements in apparatus, such as the 60-cycle converter, will tend to broaden the field of the various classes of service, but it is difficult to imagine the complete elimination of all but one class.

Total centralization up to and including the substation is feasible today. Beyond this point partial centralization must be our aim, and the nearer this can be made to approach unity, the more perfectly we, as engineers, are serving our fellow-men.

In Cleveland we have aimed to centralize as much as local conditions would permit. The transmission system to substations is radial, with two substations in tandem. One cable is installed as a reserve between the generating station and the first substation, and also one between the first and the second substation. Until recently the reserve cable was kept alive at the supply end and the switch at the receiving end was left open. We are at present installing reverse-power relays of the selective wattmeter type on the receiving end of the cables, and will hereafter operate all cables in parallel. Tests show these relays to be very effective, and remarkably free from the limitations mentioned by Mr. Merriam on page 264.

Our reserve capacity under the radial scheme varies from 100 per cent, where one cable is sufficient to carry the total load, to 25 per cent, where four cables are required.

In order to minimize investment, it has been the policy to install originally to the second substation in the tandem group, two 2000-kv-a. cables. When the load has increased beyond 2000 kv-a., a standard 4000-kv-a. cable is installed, and the

two original cables operated in parallel as one, through one oil switch at each end.

In the matter of different classes of service, when possible, both a-c. and d-c. conversion apparatus has been connected to one high-tension bus, reducing the transmission capacity required, because of diversity and improved power factor. This scheme is also followed, as far as practicable, by having one a-c. and one d-c. substation in tandem, reducing the investment in transmission between the generating station and the first substation even more than in the case of two a-c. stations, due to the greater diversity.

Power factor has also been improved by the use of synchronous condensers in substations and on consumers' premises.

The diversified routing of transmission lines has been touched upon by Mr. Gear. This is advisable whenever the investment in subway will permit, but care must be exercised to have the distances approximately equal in order that excessive loads may not be carried by certain lines, and underloads by others.

In the matter of railway load, specific cables are furnished only from the power company's nearest substation to the railway company's substation. Centralization of these stations may come in the future, but the time is not yet ripe for this accomplishment.

General distribution is at 2200 volts, three-phase delta, with single-phase lighting mains radiating from the load center, and three-wire secondaries. The large number of trees in "the forest city" makes this system of distribution much more reliable than the four-wire system.

Tests recently made on weather-proof insulation show that after a small amount of weathering the dielectric strength is less than 2200 volts, but deterioration from then on is slow, the wire withstanding safely the Y voltage to ground. Hence, the liability to electric shock is very much decreased, with the lower voltage.

Small scattered power demands are taken care of by lighting feeders equipped with regulators. Large power is carried on separate power circuits, generally not regulated. The duplication of circuits is not as great as might be supposed, as the factory lighting is carried on the same transformer installation as the power (balance coils being used); and in the manufacturing districts there is relatively little residential or store lighting, so that a No. 6 primary lighting main will often suffice.

Adjacent a-c. substations are, on the average, about 2 1/4 miles (3.6 km.) apart. This compares very favorably with the distances between similar stations in other cities using higher voltages and generally the same size of copper in their feeders.

The maximum 2200-volt load on these stations varies from 1000 to 6000 kw., depending on the district served.

The type of station now standardized is very economical in floor space. A two-story and basement building about 50 ft.

(15 m.) square is capable of distributing a load of 20,000 kw., of which 12,000 kw. may be distributed at 2200 volts and the rest to bulk customers at 11,000 volts. 1500-kw transformer banks, consisting of three 500-kw. self-cooled units, are used. I do not agree with Mr. Gear that, for substations of over 1000 kw., air or water-cooled units are necessarily most economical.

Centralization is further carried out by serving, whenever economically possible, customers exceeding 300 kw. in demand, from 11,000-volt distribution cables with a single voltage reduction at the customer's premises.

Mr. Goodwin has called attention to the equity of charging a lower rate for high power factor and a higher rate for low power factor. A contract has been in force in Cleveland for about two and a half years, which accomplishes this.

Philip Torchio: I would like to ask Mr. Merriam if he can give us some of his actual past experience and data on the effect of the three methods of increasing the rupturing capacity of oil switches, by the use of reactance, especially, and the other method that he referred to, by using the resistance in shunt with the breaker.

S. D. Sprong: I would like to inquire about the experience had with four-wire, three-phase primary distribution. In this system we have the elements of three single-phase distributing lines, and the fourth wire is necessary to maintain the stability of the system. What is the experience in every-day operation, as to the effect of interruptions and short circuits involving the fourth or center wire; as to the unbalanced pressure on the three single-phase systems; and also, in the case of an interruption to the fourth wire, how does that affect the relation of the phases and the circuit as a whole?

D. W. Roper: As far as the short circuits involving the neutral are concerned, they give no particular difficulty. The circuit breaker on that particular phase wire which is involved, opens, clears the short circuit, and the voltmeter compensators are adjusted so that they will maintain the proper pressure on the other two phases. There is a compensator on the neutral wire as well, so that the neutral drop is compensated independently of the drop on the phase wires.

On the question of the neutral opening near the station or some place so as to cause an unbalancing, I do not recall that we have ever had any case of that kind, that involved any great portion of the circuit. There have been cases occurring in the outlying portions of the circuit, which involved a few customers only, but in general the neutral of the feeder, near the station, is a large wire and is generally an underground cable.

On the question of troubles involving short circuits and overloads, we have recently been trying a little heavier setting of the relays, that is, we have been abandoning the idea that the relays protect from overloads. We set the relays so that

they protect from short circuits only, and find that we give very much improved service, without any offsetting disadvantages. We have by the use of the heavier setting cut out such a large proportion of the interruptions due to ordinary overloads or to no apparent cause, that we have a fixed rule that when the circuit breaker opens automatically in the substation twice or more in rapid succession, a patrolman is sent out to find the trouble, and in over seventy-five per cent of the cases he finds the trouble.

E. M. Hewlett: The question of relays has been considered so generally that one might think they were all alike. Many people seem to think that a relay, because it is a relay, will do whatever they desire it to do. Others, however, and particularly those who have made tests of relays on electrical systems, realize that to get proper results from a relay it is necessary to have a rational piece of work for the relay to do, to know the limits of its operation, what it is expected to accomplish, and besides, to have no extra circuits that conflict with the regular operation of the relay and upset the sequence of operation.

Then there are quite a number of systems which have been laid out with the expectation that relays would take care of all the troubles. Now, when the systems are too complicated, that is, have too many side paths, it is difficult to obtain proper protection. A more direct study of the problems involved, of the possible current flow in different directions, etc., should be made in connection with all these relay problems. I believe most of them can be taken care of, but in cases where this cannot be readily done, the system should be changed so that it becomes a practicable system. Some systems are actually impossible for continuous operation, on account of the connections, etc.

In reference to oil switch capacity, which Mr. Merriam brought out, an oil switch can be made for almost any duty, but it is, I think, rather, a question of the amount of energy which it is advisable to connect on any given system. There are magnetic strains in the system which will draw the conductors together and cause numerous troubles, and it depends on how much of a strain you wish to design your system for, how high a duty switch you desire, and how much money you put in the lines or systems. It seems as though 50,000-kw. sections would be about right, but you can run considerably above that with limiting reactances and with feeders so arranged that the energy flow under short-circuit conditions is reduced to a reasonable amount.

I wish to make a point about the so-called "safety first" movement. There seems to be a tendency in some quarters to go to considerable length to protect all circuits that are alive, irrespective of their location or the conditions under which they operate. Many people are of the opinion that *all* live wires should be covered and protected so that they can-

not be touched. Obviously this is going too far. While it is true that great attention should always be paid to the protection of human beings from injury, this idea should not be carried to extremes, and before making blanket decisions in this matter, a careful study of the conditions should be made.

In a manufacturing industry, for instance, there may be employed a thousand or more men to every thousand kilowatts of power used to operate the machinery, and practically none of the men conversant with the danger of touching live electric wires running to the various machines. Here the hazard is apt to be comparatively great, and it seems advisable to go to considerable lengths to safeguard against the hazard prevalent owing to the conditions.

In a central station, however, or wherever the live circuits are accessible only to those expert in their use, and fully cognizant of the danger of contact with them, it appears rather unnecessary to introduce many detail or minute measures of safety. In such an installation the ratio of men to kilowatts may be only one to a thousand, and besides, the chance of injury from accidental contact, in contrast to the manufacturing installation, very small. It thus seems, then, that where switchboards are under trained supervision and kept isolated from others, little further need be done to bring the degree of hazard much lower than it is now.

In reference to 2400-volt d-c. circuit breakers, etc., for railway work, the Butte and Anaconda line has been working quite a while now with a magnetic blow-out type of circuit breaker, but with the magnetic fields on both sides. The same kind of breaker has also been designed for a 3500-volt equipment for a French railway. Enough experimental work has been done on 5000 volts to show that the 5000-volt direct-current circuit breaker is also a practicable device.

H. R. Summerhayes: In Mr. Torchio's paper it is stated that the mains in the Edison three-wire system are always made the same size. I would like to know if experience has shown that on account of burn-outs, etc., it is actually necessary to make the neutral the same size as the outside wires. It is further brought out in Mr. Torchio's paper that, in spite of making the neutral the same size as the outside in the mains, the arrangement of the neutral in the feeders is such that the currents are balanced, and the total neutral copper is only 16.9 per cent as against 83 per cent for the outside wires.

In Mr. Gear's paper some mention is made of systems permitting the operation of cables in parallel to substations, and I would say that if all cables can be operated in pairs a balance relay system is available which will in general give very good protection. Of course, a large installation requires special study to see that all conditions are met. In reference to substations, it is probable that some saving could be made by automatic substations, in the case of the smaller stations.

Mention is also made in Mr. Gear's paper of the three-phase, four-wire secondary network. This is used to a greater extent abroad than in this country, but it appears to have certain advantages. I believe a study would show that it could be used to a greater extent here, to advantage.

Philip Torchio: Where full main neutrals are used they serve as well as feeder neutrals. Besides, the size of the neutral of the mains involves a question of securing a high degree of regulation. To explain: on the side where you have the heaviest load you have the heaviest drop, and, as the unbalanced load will come in on the neutral, if you make the neutral small you will exaggerate the drop on the loaded side. The Edison three-wire system of distribution has been designed with the greatest degree of liberality. While on a railroad system a poorer regulation may be permissible, our system requires very close regulation and, therefore, justifies greater liberality in the use of copper.

John B. Taylor: I ask Mr. Torchio just what he has in mind in referring to difficulties with the diametrical connection of synchronous converters—the diametrical as distinguished from the double delta connection? This diametrical connection has been in regular use in railway service for the last ten or twelve years, and while I cannot speak so well for the lighting field, I know that it has been on lighting converters for at least eight or nine years. The advantages of such a connection are, of course as obvious now as they were at the time of its introduction, and I do not see why there should be any special conditions in the lighting service that should delay for ten or twelve years the adoption of a connection which seems to possess such pronounced advantages over a connection that has been used largely as a matter of chance, I think, previous to that time.

I should like to hear from Mr. Merriam regarding what is, perhaps, a misstatement as to the function of the oil switch in interrupting a circuit. The switch is to interrupt the circuit and the idea is, in addition, to make a switch so that no absorption of energy by it will occur. Unfortunately, it seems to be true, with switches as they are constructed, that it is impossible to avoid dissipating a certain amount of energy in the switch itself, but I cannot see that there is anything inherent that calls for the dissipation of energy in the switch, nor why the switch cannot be so designed that the energy does not have to be dissipated there. A parallel case is when you have water in a pipe. You may have any quantity of energy stored in your reservoir, back of the point in the pipe where you wish to interrupt the flow, and the mere closing of a valve does not necessarily absorb any considerable portion of the energy thus available, and I think, at least on paper, it should be possible to design a switch in which the energy absorbed or dissipated in the switch, at the moment of interruption, could be negligible. Practically, I do not wish to say that we are anywhere near doing that, but it seems to me there is a proper distinction there which should be kept in mind.

On the railway feeders, without going into details, it seems to me that the distribution network must meet two conditions. The first condition is that the railway trolleys, feeders, third rails, etc., must be more or less interconnected in order to work the conducting material at a fair economy, and also it must be possible to have them separated so that under operating conditions a short circuit at one point will not tie up things too extensively. This, of course, results in the various feeder systems, various devices for switching feeders, circuit breakers, etc., which must be placed along the line.

I see no specific mention in any of these papers of the use of the so-called "automatic sectionalizing switch"—a device which may be put on the line to tie together two feeders or sections of trolley wire or third rail, both of which are alive. These switching devices connect together two or more feeders, provided they are separately energized from the same or different substations, and in case of a short circuit, or in case of a desire to interrupt the power, merely by interrupting power supply to both feeders, at the substation or at the power station, these disconnect themselves, at which time power can be restored on one without restoring it on the other. Of course, this scheme is not universally applicable, yet there are so many cases where it would effect such marked saving in copper that it would seem to merit more specific mention.

I want to raise a question in connection with what Mr. Murray has to say about the single-phase distribution. The principal point he mentions is the one-wire single-phase railway transmission system. If we can believe the evidence of our eyes in riding over the New Haven road, it is clear that a change in that distribution system has been made, or is in the process of making. I trust Mr. Murray may have something to add on this point to reconcile the discrepancy between what is done, or done in part, on the representative single-phase road, and what he states is the desirable way of doing it.

Mr. Lincoln, it seems to me, has missed the real reason for the series lighting system. I do not think that the desirability of throwing the switch on at the power house to turn on all the lights on the street is by any means the controlling reason which brought about the series system. The series system came about through the inherent characteristic of the carbon arc, the property which has been commonly called "negative resistance", which meant that it was necessary to have controlling devices to keep the current within a proper value, and it was a much more economical proposition to do this either by the design of the machine at one point, or other controlling means, at a central point, rather than by individual steadying means at the lamps. Also we should remember that the arc light started as a d-c. instead of an a-c. system, so that it would have been out of the question to distribute at low voltage with an economical amount of copper, and out of the question to distribute at high voltage without

inserting the necessary transforming devices for individual lamps. So far as the d-c. arc is concerned, these conditions seem still to control.

The point I want to make is that the series system came in for good and sufficient reasons, which are other than the desirability of turning lights on and off at one time.

At the present time, with the ability to run tungsten lamps of high candle power on alternating-current circuits quite as well as on direct-current circuits, it looks as if the separate series circuit with the separate cables or ducts from the generating station had little excuse for continuing as the only street lighting system.

E. W. Trafford: With reference to Mr. Lincoln's paper on arc lighting distribution, I want to say that a few years ago, in a station which now has about 2000 arc lights, I saw that we were filling our streets with a large number of small wires, and recognized the desirability of reducing the number of wires and using those of larger size. A great many years ago a system was devised which made use of constant-current distributing transformers. I have used that system for the past three years with considerable success, with circuits of 200 arc lights, using 30 amperes constant current at 4000 volts.

Instead of distributing current single-phase, a three-phase star connection with series transformers in each leg may be used, in which case, with the same current and voltage, the circuit would be of 250 kv-a. capacity. Such a system has many advantages with both overhead and underground distribution, perhaps more noticeably for underground distribution, where a few cables of convenient size can be placed in the ducts in place of the multiplicity of small cables usually employed. The system also offers great advantages in a mixed underground and overhead distribution. It is easy with this system to install a transformer and drop underground at any point and operate a separate series circuit of the desired voltage and current.

Instead of using constant-current regulators or transformers as they have heretofore been used, they may be employed merely as regulators in connection with ordinary static transformers. With a number of transformers on a given line it is improbable that all of the secondary circuit would open at one time and consequently the same percentage of regulator capacity is not necessary. By this means the power factor of the system can be very much improved.

In the station the substitution of a few devices of moderate capacity in place of the multiplicity of small apparatus results in a simplification of switchboards which is very apparent. In some cases, as in the one cited, the use of this system eliminates the necessity of a substation.

Objection to such a system in the past was based on the fact that transformer design was not as well understood as it is now, and that, upon the secondary circuit becoming open, a large rise

of potential would follow, causing burn-outs or establishing a dangerous condition upon the secondary circuit. But in these days of automatic devices it is very simple to arrange automatic switches which short-circuit the secondary, either upon a rise of potential occurring or upon the interruption of the secondary circuit. In the installation referred to, twenty-five transformers have been in service for about three years, without difficulty or the loss of a single transformer.

With this system it is possible to run a few well-insulated supply mains throughout the length of a city, and at convenient points install transformers operating short series underground lines, at moderate voltage, thereby making it commercially practicable to furnish underground street lighting service even in communities of moderate size.

J. T. Kelly, Jr.: There are one or two things which we are doing in Baltimore, that, from the standpoint of the operating engineer, may be of interest to some of you gentlemen.

For the reason that has been mentioned several times, we are in the position of having to furnish as near absolutely perfect service as possible. One of the troubles which we have experienced is that of feeder interruptions. The induction motors, even though the feeder may be restored in a very short length of time, will drop out and we have some complaints from customers on that account. It has been thought that if the feeder could be restored to service quickly enough, that trouble could be obviated. Experiments have been carried on with an auxiliary relay of the wattmeter type which operates to close the feeder switches as soon as they open, and it has been found that, with reasonable certainty, the switches can be closed within seven-tenths of a second from the time they start to open, or, putting it another way, on 60-cycle service, well within 40 cycles, and that there will be practically no rush of current to the induction motors, no interruption to the service, and as far as the lighting is concerned, merely a very slight flickering. This was the idea of our Mr. F. E. Ricketts, who has carried through the experiments and reached the point where the system is about to be put in operation in one of the principal substations.

It will also have a very important use in outlying substations in the suburbs at which an operator is not ordinarily in attendance. I ought to say, in that connection, that these relays may be so set that they will close a circuit once, and if it drops out again, remain out, or they may be set to close the circuit two or three times, or as many times as you like, before remaining out.

The question of locating faults on underground cables is always a very troublesome one. It came to our attention, through our friends of the local telephone company a year or more ago, that certain of our frequency changers, operating at 2300-4000 volts, had such characteristics that there were present,

in the neutral, harmonics which caused a disturbance on the telephone lines. A study was made, and it was found that the thirteenth harmonic was present to that extent, and steps were taken to change the characteristics of these machines. The idea occurred to some one, however, that that might be made use of in the locating of underground cable faults, and it has been made use of. The method is to connect a machine having this characteristic in a marked degree to a spare bank of transformers, preferably of large capacity, and connect the faulty cable in series with the neutral between the machine and the transformer bank. If the cable is broken down between conductors, a dead short circuit, two conductors may be used; if it is broken down to ground, one conductor and the lead sheath may be used. Since we are trying to get rid of that characteristic in our machines, it was necessary to rig up a small set, of about 5 kw. capacity, which we ordinarily use for that purpose with much success.

The method of finding the fault after the connection is made is by means of a small finding coil in series with a delicate telephone receiver. It is only necessary to go into the manhole and hold the finding coil close to the cable. If you are between the station and the fault, the harmonic is present, and you readily hear the tone in the telephone receiver, which is a very different tone from the general tone of the system, and readily discernible. The moment you get beyond the fault, you fail to hear the tone.

John Murphy: I have read of such a scheme being employed in Berlin, and a friend told me that it was not necessary to enter the manhole. The sound is detected walking along the street. I would like to ask Mr. Kelly if he has heard of that system or used it.

J. T. Kelly, Jr.: On our distribution feeders we have adopted the method of placing an expulsion type fuse between the main feeder and practically all the principal taps from the main line. These have the advantage of acting as disconnecting switches, if desired, as well as of clearing the main feeder of trouble, instantly, when trouble occurs on one branch.

Our company has spent considerable money to perfect a system, both in the overhead and underground portions of the a-c. territory, of tying in adjacent feeders through oil switches at as many points as possible, within reason. We use oil switches in every case, properly phased out beforehand, and in connection with this scheme we furnish each of our trouble men with a small pocket-size loose-leaf binder, carrying bulletins of various information, and many other things, including diagrams of the emergency connections of each feeder, so in case of trouble it is not necessary to get hold of some one who may be familiar with all these points, or may be familiar with the record of them. Each trouble man has in his pocket the specific direction which will enable him to restore service in the

shortest possible length of time. At frequent meetings the trouble men are coached and quizzed on these points to see that they are kept in mind.

There is another point in connection with that—the tying in of feeders on the outside may be considered in the light of a station switch of which the station operator has no knowledge. We have found it a very wise thing in every case to advise the station operators, in advance, of such and such a switch, so they may know what to expect, otherwise the performance of their instruments, regulators, etc., may be very misleading to them.

I notice the statement which was made in regard to the Commonwealth Edison Company, that in case of a short circuit on one phase the breaker on that phase will open and the other phases remain in operation. We have not been able to do that, with success, for the reason that we have a great deal of three-phase load on our distributing feeders, and we have found that, when we attempt to operate two phases of a four-wire feeder, the third wire being dead-grounded or short-circuited with the neutral, we blow the fuses on our three-phase banks of transformers and get into a good deal of trouble. Our breakers are therefore locked so that they operate together.

H. B. Gear: Answering Mr. Kelly's question, the difficulty mentioned is avoided in the Commonwealth Edison system by not connecting the neutral of three-phase installations to the neutral of the system. When this is done trouble on one phase cannot be communicated through the transformers to the other two phases. This has entirely remedied this sort of trouble, in Chicago.

Carl Schwartz: The distribution of electrical energy in a certain territory is a natural monopoly. Competition is bound to lead to a duplication of facilities, resulting in less density of load per unit and a less favorable diversity factor. This condition also suggests pooling existing facilities. Any wastefulness in this respect, as well as in the design or development of a distribution system, will ultimately fall upon the public, either the company's stockholders or the consumer, who will have to pay a higher price for the product. When it is further considered that the cost of power at the busbars of the power station is generally below the fixed charges, operating and maintenance expense for its distribution, it will be seen that the economics of distribution deserve careful attention.

The distribution system of one of the railroad companies in New York City was designed after a complete analysis of practically all possible combinations of feeder connections and distributions of substations in order to arrive at the most reliable and economical combination. The system can be briefly described as follows: Primary three-phase alternating current at 25 cycles is distributed from two power stations at 11,000 volts to nine substations located from about 3.8 to 8.6 miles (6.1 to 13.8 km.)

apart, delivering direct current at about 660 volts to the third rail. Seventeen high-tension lines connect the two power stations directly with the substations, the latter being interconnected by tie lines.

All substations are supplied by not less than two independent lines and are equipped with three or four synchronous converters of either 1000, 1500 or 2000 kw. capacity, and in some cases, where continuity of service is of prime importance, with storage batteries. The direct-current feeder system connects the substations to the third rail through circuit breakers under remote control from the substations. The third rail is sectionalized throughout by the circuit breaker connections, the breakers being installed in thirty-two separate buildings, located from about one-half to two and one-half miles (0.8 to 4 km.) apart throughout the electrified territory, which extends over a total distance of about 51 miles (82.2 km.). The fixed charges, operating and maintenance cost of this system, including storage batteries and third rail, are, with the cost of current at the power stations busbars, in the ratio of about 1.3 to 1, which shows that this distribution system for d-c. railroad operation is economically designed.

The engineering features of a distribution system are so closely related to the generating system and its location, and to the distribution and character of the load, that a determination of the distribution system alone, without due consideration of all other portions, will lead to erroneous results. One system may permit the generation of current more economically and with a greater degree of reliability than another. For instance, large quantities of electricity are produced and distributed under more favorable conditions in the form of three-phase current than in the form of direct current or single-phase alternating current. At the point of consumption alternating current may be acceptable under some conditions and not under others; for instance, dense city service for light and power practically demands the insurance of continuity of service by storage batteries.

The efficiency of the distribution system alone, from an investment, operating and maintenance standpoint is, therefore, not conclusive evidence of the wisdom of its selection, as its advantages may be counterbalanced by disadvantages incidental to the generation and application of the product. Hence, a proper comparison can only be made by analyzing from the coal pile to the point of delivery, whether the ultimate form of power be light, a motor pulley, the drawbars of a locomotive, or something else.

Appendix VII, on a-c. distribution for interurban and steam railroads, differs from the others in that it does not illustrate present practise, but offers the use of a single a-c. trolley wire as recommended practise. If this question was as simple and easy to answer as done in the paper, probably many of us would be thankful to Mr. Murray for the relief from a good deal of work.

The speaker does not wish to be understood as wanting to

detract in any way from the merits of the system Mr. Murray advocates, as it may, under certain conditions, produce results equally as good as or better than others. It is noted, however, that in drawing his conclusions Mr. Murray omits any reference to the matter of current supply and its complications, and apparently overlooks the fact that other forms of current on a trolley wire will likewise give satisfactory results, and will even avoid the necessity of carrying some equipment of the distribution system on the locomotives. If Mr. Murray should ask for a quotation for the delivery of single-phase power for railroad service, he would probably find that he has to pay an appreciably higher price than for three-phase current.

Mr. Blair refers to the important matter of electrolytic action. This question has been given very careful consideration by one of the railroad companies in New York City during the past few years. Exhaustive measurements of current and potentials have been made and recorded to determine the flow of current in steel structures, cable sheaths, pipes, etc.

A system of protection was developed which has made the structures likely to be affected as free from electrolytic action as possible, and it has been determined by laboratory tests and field investigation that the slight amount of current flowing is either too small for any appreciable effect or it has been so directed as to be inactive.

Insulated negative return feeders contribute to the prevention of destructive electrolytic action, yet, unless they are so connected as to produce fairly uniform pressures at the track, they do not bring about the desired result. To accomplish this, the loss in the feeders has to be balanced either by resistances or by boosters, and the cost of the insulated negative system thus increases rapidly with an increase in uniformity of pressure.

The subject requires considerable study from case to case to determine whether this system, or other methods like the drainage system, or a combination, is preferable. Structures can frequently be sufficiently protected by directing the flow of current so that they are negative to the running rail, and this method has, to a large extent, and successfully, been followed in the case to which I have referred.

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RECORDING DEVICES

BY CHARLES P. STEINMETZ

ABSTRACT OF PAPER

The author calls attention to the importance of keeping records in electrical systems and points out that proper records can be secured only by automatic recording devices, largely because of the uncertainty of the personal element in times of accident or stress. The three types of recording devices in general use are those having a revolving disk, those using an endless tape or photo-film, and the multi-recording device on which no record is made of normal operations and on which the record sheet moves only when a record of abnormal occurrences is being made. The revolving disk machines produce such condensed records that a sequence of rapidly fluctuating events cannot be distinguished, while the curve-drawing instruments, if the tapes were run rapidly enough to show all the fluctuations, would produce records of such enormous length that they would be impracticable to operate commercially. With the multi-recorder the record is made in a very condensed and handy form and its accuracy in respect to time is very high, so that the sequence of events recorded can be checked within a fraction of a second. The latter instrument, therefore, is adapted to produce minute and accurate records of all phases of station operation.

WHILE the keeping of records is essential in any business, it is especially important in the operation of electrical systems, and thus records have always been taken of voltage, current, power, of the time of starting or stopping generators, etc., in electrical systems.

Perfect reliability, however, can be secured only by automatic recording devices.

For instance, where it is the duty of the station operator to keep constant voltage, the voltage record made by noting down the voltmeter readings at constant periods of time would probably show uniformity, while an automatic recording device may show bad fluctuation between these times. A protection against neglect or carelessness of taking records, and a check on the operating force, is afforded only by automatic recording devices. But especially when things go wrong, when accidents happen, and the necessity of action interferes with careful ob-

servations, the human machine more or less breaks down and only automatic devices are reliable in recording the events.

Automatic recording devices are therefore extensively used: Revolving-disk recording voltmeters, ammeters, thermometers, steam flow, meters etc.; curve drawing instruments; the oscillograph.

In the revolving-disk recording meter, a 24-hour, or 12-hour record is made on a circular chart. The shortest time interval, which can, under industrial conditions, be accurately noted on these instruments is not much less than a quarter of an hour. Where the quantity changes slowly, as the temperature of a room, a clear chart is given. Where, however, more rapid fluctuations occur, as with current and often with voltage, the chart shows only a broad blur, and neither the individual variation nor the sequence of events can be seen, but merely the maximum and the minimum values estimated.

Curve-drawing instruments, in which an endless tape moves with greater or less rapidity, in front of the recording pen, are used for records of more rapidly changing events, as current, voltage, speed, acceleration of a rapid transit train cycle, etc. But to take a continuous record of an interurban railway substation by a curve-drawing instrument moving with sufficient rapidity to show all the fluctuations, would be feasible only in special investigations; but the enormous length of the record would exclude it in commercial operation.

One of the most rapid recording devices is the oscillograph, and its use has been of material assistance in electrical development, for instance in giving information on momentary short-circuit currents of alternators, on the performance of circuit breakers and other problems, upon which information could be derived in no other way. But the taking of a continuous record of station operation by oscillograph obviously is out of the question.

While automatic recording devices are necessary in the normal operation of electric systems, they are still much more essential under abnormal conditions, when things go wrong, and accidents happen. Usually no serious difficulty exists in designing apparatus to operate satisfactorily under normal conditions; also no serious difficulty exists in operating a system under normal conditions, but to meet the abnormal changes of accidental conditions is the serious problem of the electrical designer and of the station operator.

We really know relatively little of the abnormal conditions which are met in electrical operation, and most of our knowledge is rather theoretical, representing what might happen; but exact information of what actually happens is extremely limited. When some accident happens, whether it be the failure of a transformer, or the shut-down of a big system, usually an investigation is made, reports called for, and the witnesses cross-examined. But the information gleaned from these examinations is practically always unsatisfactory and incomplete. Frequently no trained observer was present, or so many things happened almost simultaneously, that most of them could not be observed. The circumstances are very unfavorable for exact observation. The necessity of immediate action excludes close observation and almost always excludes immediate

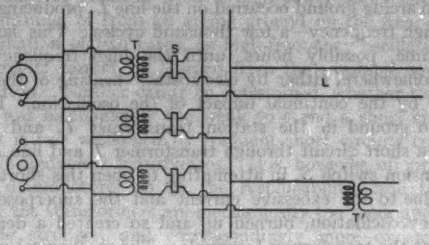

FIG. 1

noting of the observations, so that the record must be based on the memory of the observer, which is not very reliable in times of excitement. The personal element also comes in, the natural tendency toward avoiding personal responsibility for the accident. The sequence of the events, which is all-important for the understanding of their cause, is rarely noted in the excitement, and thus such examination hardly ever definitely fixes the cause of the accident, without the necessity of very extensive guessing of more or less questionable reliability. It is, however, of the greatest importance to the operator as well as the manufacturer of the apparatus, to know exactly what happened, so as to guard against its recurrence, and to fix the responsibility.

For instance; in a large high-voltage transmission system, partly illustrated diagrammatically in Fig. 1, a big transformer T in the generating station, a high-tension switch S in the gen-

erating station, and a transformer T' at the end of a branch line, are destroyed. At the same time a flash-over occurs on the transmission line L.

Postmortem examination of the transformer showed numerous arc burns on coils and on the tank, and the coils badly deformed and bent out of shape. Questioning of the operators elicited the information that lightning had been frequent during the period preceding the accident. One operator believed he had noticed static in the station for some time before the accident. It is suspected that numerous short circuits have occurred in the lines during the weeks preceding the accident.

This information is altogether too meager to find out beyond doubt what actually happened. We can only theorize what may have happened, for instance:

1. An arcing ground occurred on the line L, producing moderately high frequency—a few thousand cycles. This lasted for some time, possibly hours, until the high frequency broke down somewhere, either by electrostatic heating of the insulation, or by the continual impact of the oscillation. It broke down to ground in the station transformer T, and thereby caused a short circuit through transformer T and line L. The high-tension switch S, in attempting to open this short circuit, failed, due to the excessive current and the superposed high-frequency oscillation, burned up and so created a dead short circuit at the transformer terminals. The mechanical magnetic forces resulting therefrom in the transformer, moved the coils. The shock of the short circuit broke down the transformer T' at the end of the branch line.

2. Numerous flash-overs had occurred during the preceding weeks in the transmission lines, resulting in heavy short circuits. While the transformers were strong enough to stand occasional short circuits, the short-circuit stresses were so enormous, that continual short circuits gradually impaired and finally broke down a transformer T. This resulted in the destruction of the circuit breaker S, the failure of the second transformer T', etc.

3. Lightning entering the line L started a high-frequency cumulative surge in the transformers, producing spark discharges between the coils. The same or another lightning stroke flashed between the lines, caused a short circuit, resulting in the destruction of the circuit breaker. The spark discharge in the transformers finally led to short circuit, which distorted the transformer coils.

4. An internal oscillation in the transformer, due to entrance of high-frequency lightning, or resulting from an arcing ground on the line, caused spark discharges in the circuit breaker, leading to its destruction. The short circuit resulting therefrom, moved the transformer coils and brought them sufficiently near to either end of the tank, to cause arcing over, with the resulting destruction of the transformer.

Numerous other combinations of the phenomena could still be devised, to account for the accident, for instance, the transformer T' at the end of the branch line may have broken down first, and the accidental arc may have produced the high frequency, which damaged the circuit breaker and main transformer, and flashed over the transmission line, etc. But whether the trouble started with a high-frequency oscillation in the transformer, or resulted from a high-power short circuit, or from lightning, or from an arcing ground on the line, or from a combination of two cases, as high-frequency oscillation and short circuit, cannot be learned from the available sources of information. Neither can it be determined, whether the transformer was mechanically too weak to stand a short circuit, or whether it was weakened by frequent short circuits combined with high-frequency disturbances. It is, however, of importance to the manufacturer to fix the responsibility, and to know whether the transformers are mechanically too weak and should be made stronger, and correspondingly more expensive, or whether and what additional protective devices should be developed. And it is of still greater importance to the operating companies, to take such steps as will insure reasonable reliability of operation.

If automatic recording devices would show what happened and the sequence of the happenings, whether the trouble started with lightning, or with an arcing on the line, or a line short circuit and how this originated, or a transformer surge in the generating station or the branch line, etc., then in most cases the phenomena could be exactly determined, and with reasonable certainty precaution against their recurrence taken. Also, less difficulty would usually be experienced in fixing the responsibility on the manufacturer of the apparatus, or on the operating engineer, or on *vis major*. As it stands at present, the transformers are rebuilt with greater mechanical strength, and damping devices against transformer surges installed, and it is "hoped" that the phenomena against which these guard,

were the causes of the trouble, but we cannot possess the confidence that the same will not happen again, and if similar troubles do occur again, it merely means that some of the other various possibilities were the initial cause of the trouble, and that the remedy would lie in the installation of an arcing ground suppressor, or in grounding the neutral, or in disconnecting the grounding of the neutral, or in reducing the sag of long spans to eliminate the swinging together of the lines, or in adding another disk to the suspension insulators, or in better weeding out defective insulators by high-frequency testing, etc.

Numerous such instances could be given. Thus, in underground cable systems, breakdowns occur frequently in groups, or practically simultaneously, and it is difficult to determine which cable started the trouble. For some time, often days, troubles with feeders may have preceded the breakdown, and if properly recorded, would explain its cause and so give a greater probability of guarding against its recurrence, etc.

The difficulty or impossibility of getting complete and exact records of what happens in electrical systems, and of the sequence of the events, is the most serious limitation, at present, to providing protection for such systems.

Automatic recording devices thus are of the greatest importance for the safety of operation of a system, especially where reliability is important. However, in case of trouble, the sequence of events commonly is so rapid, within seconds or less, that such devices must be capable of recording within fractions of seconds. The dial instruments, like the revolving-disk recording meters, therefore, are out of the question, as they show everything within a few minutes as simultaneous. Curve-drawing instruments would have to run the tape rather rapidly. If we assume that 50 records are needed, and allow between $\frac{1}{8}$ and $\frac{1}{4}$ in. per second as the minimum, about 15 miles of tape would be unrolled per day, and to look all this over to see the records, obviously is impossible, especially when it is desirable to go back for weeks to see what has preceded. With phenomena like lightning, where several strokes may occur in one minute, and then no record for weeks or months, obviously any recording device with continuously moving tape is impracticable. Where records are made at more or less infrequent intervals—sometimes, as with circuit breakers, at fairly regular intervals, and sometimes, as with lightning discharges, at very irregular intervals—an instrument in which the tape

does not continuously move, but, as in the typewriter, moves only when making a record, is essential.

To give reasonably complete information on the station performance under normal as well as abnormal conditions, records are required of the closing and opening of every circuit breaker, of the operation of the lightning arresters, of the appearance and duration of high frequency in the lines, of grounds and short circuits, possibly of excess currents, of over-normal and subnormal voltage, frequency, etc., etc. Considering then, that even a small station may connect two or three lines, and each line has three phases, and a separate record of each phase is necessary, it is obvious that a considerable number of records is needed. With a stationary record sheet, moving only whenever a record is made, 50 records can easily be taken on the same sheet, and a 50-point multi-recorder thus appears as a convenient unit. In such a device, a sensitivity of at least $\frac{1}{4}$ to $\frac{1}{2}$ second is desirable, so that phenomena following each other at intervals of $\frac{1}{4}$ second or more, are separately recording, while everything which occurs within $\frac{1}{4}$ second appears as of the same time. Such high sensitivity is desirable to get the sequence of events which to the observer may appear simultaneous, as the breakdown of a number of feeders, etc. At the same time, such great rapidity of action requires a powerful mechanism, and, considering that the operating mechanism must be capable of working very many thousand times without failure by wearing out, the problem in the development of such an automatic multi-recorder was rather a difficult one. Also, when a record comes in within less than $\frac{1}{4}$ second from the preceding one, while the record sheet is still moving in receiving the previous record, the second record would blur, and this difficulty thus has to be overcome by retarding the second record until the taps have come to rest.

On such a multi-recorder print, one record point should be reserved for recording standard time at fixed intervals, thus giving the time correction of the clockwork which operates the recorder, so as to make it possible to record the sequence of events occurring almost simultaneously in distant stations and noted on different multi-recorders.

A description of this instrument is given by Prof. E. E. F. Creighton, in the A. I. E. E. TRANSACTIONS, Vol. XXXI, 1912, p. 825.

Discussion

Charles L. Clarke: Dr. Steinmetz has referred to the taking of continuous records by the oscillograph or other curve-drawing instrument, in which a photo-film or a paper tape is reeled off at a constant speed to maintain uninterrupted the time-element of the record, and he has in general called attention to the obvious impracticability of using an apparatus of this character adapted for recording events that may happen at quite widely separate times, such, for example, as the normal switching operations in an electrical system, and which, furthermore, is adapted to record with sufficient accuracy as to time, a very rapid sequence of events, such as a succession of operations by automatic switches brought about by abnormal or accidental circumstances, or which will at least give a definite indication as to which event happened before all the others of the sequence.

We are, nevertheless, generally accustomed to curve-drawing instruments in which the time record depends upon the constant progression of a tape, or its equivalent in the form of a rotating paper disk. But in order that the record may not be of practically immeasurable size and commercially out of the question, sacrifice of close accuracy in the time record has to be made by running the tape at a very slow speed. Thus a rapid succession of recorded events is merged indistinguishably together as if but one event had happened, and naturally there is no way of finding out which occurred first.

In the multi-recorder a radical departure from the old way of continuously recording time by constant motion of a tape and superposing thereon the happening of other events, when they happen, has been made, and in its place has been substituted the method of simultaneously printing upon the tape when at rest, the occurrence of a particular event and the time at which it takes place, followed by a slight progression of the tape to receive the record of the succeeding event and time it occurs, and so on.

This is all the record that is needed, when vital events to be noted are not of a continuous or flux character, but take place at definite and recurring instances of time, as, for example, in switching operations, for recording which the instrument before us was primarily designed. The record is kept without the use of an inordinate length of tape and is in fact in a very condensed and handy form; nevertheless, accuracy in respect to time is insured to a very close degree. This is the fundamental merit of the apparatus, which has in this instance been reliably put in practical form by skilful attention to mechanical and electrical details.

The applications of the multi-recorder that are apparent are many, and numerous other uses for it will doubtless be found from time to time.

In the paper describing the device, published in the A. I. E. E.

TRANSACTIONS, Vol. XXXI, 1912, p. 825, abundant evidence is given of its value for recording switching operations in an electrical system. The record made under normal conditions is a watch over the proper performance of duty by the switchboard attendant, while under accidental and abnormal circumstances the instrument not only stands guard over the attendant to record his correct moves, or his blunders, but may be adapted to pick up and record the shortcomings of the system in respect to the matters that are outside his jurisdiction, or his ability to control.

Its action is so rapid that the sequence of operation of oil switches can be noted. Time-element relays can be checked to the nearest second. Duration of accidental short-circuits and surges can be recorded. It notes whether a feeder is alive, and if so, the time when, and initially from which end, it was energized. It may keep watch over the care of aluminum lightning arresters in respect to charging them properly and at correct intervals, and that they are not abused by charging them for too long a time. The connections of the multi-recorder can be used to make the load dispatcher's dummy switchboard in a power station automatic. More rapid switching can be carried on, as the exact conditions are always before him. Signals and responses from one part of the station to another can be recorded, also starting, synchronizing and stopping generators, operation of ventilating motors, and various auxiliary apparatus. Determination of the value of the overhead ground wire of a transmission line by recording the lightning strokes (ordinarily recorded by puncturing paper) is feasible, in which application the instrument would take the place of a large corps of observers located along the line, and with elimination of the confusing uncertainties of many observations tempered by the personal equation of different individuals. Its reliability and utility in practical service have already been fully demonstrated for those of the foregoing purposes to which it has been thusfar applied.

The probable utility of the multi-recorder in automatically noting the time and duration of application of successive steps in manufacturing processes suggests itself; it might be a process for making insulating material, requiring exact intervals of application of current potential and heat, or processes in a chemical works, or in refineries, etc. It might be applied in boiler rooms of large power stations to check the testing of gages, the opening and closing of valves, dampers, firing operations, etc.

The operations going on in railway switch towers at important crossings and at large yards and terminals are easily within the ability of the instrument to record; likewise record may be made at headquarters of the calls from police telephone and fire alarm boxes.

Tally can be kept on the operation of some machine tools,

for instance, punch presses, to insure that the normal output is forthcoming.

The time when employees come on and go off duty can be centrally recorded.

We have before us the 24-hour power log of a cement manufacturing company, in the form of a large sheet ruled off vertically for time, and horizontally for apparatus, and for various other data, the record of which is to be noted each hour. The record for "apparatus in operation," includes engine-driven generators, exciters, air compressers, condensers, pumps, stoker engines, boilers, and fifty-one motors; there are also places for record of load curve, wattmeter readings, general data, miscellaneous readings, coal data, and crews on duty.

This log is filled in daily by hand. The record for all the apparatus noted above could be made by a multi-recorder, and also that for the crews on duty. The application would in this instance be easy, and not necessarily call for an automatic electric contact device on the apparatus to cause a record. The duty of the man on the job would simply be to press one electric button when an apparatus was started, and press another when it stopped. This I believe would insure proper attention to duty in most cases. The man would know that his record was made beyond his ability to alter it, when he pressed the button, and he would be likely to see to it that the record was made at the right time. If, however, circumstances should make it important to record the operation of apparatus beyond any doubt, a suitable electric switch device could be applied thereto; this would absolutely prevent tampering with the time recorded. The log now used presents every opportunity for tampering, to the extent that the operative learns from experience what can be done without detection; it also offers a chance for errors resulting from not making a record at the proper time, but neglecting so to do and trusting to memory to fill it in at a later time. The face of this log is an additional suggestion of possible fields for the commercial application of the multi-recorder.

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THE PRESENT STATUS OF ALUMINUM-CELL LIGHTNING ARRESTERS

BY E. E. F. CREIGHTON

ABSTRACT OF PAPER

This paper gives a brief survey of the conditions of operation of aluminum-cell arresters, without any description of the forms of the arresters. References are made to recent investigations of lightning phenomena and their possible effects on the design of protective apparatus used at present. The d-c. aluminum arrester is most economical and represents the highest possible grade of protection. In connection with the a-c. aluminum arrester the following points are discussed: dielectric spark lag, dissolution of film, charging resistance, oscillations, damping, degrees of surges due to natural operations and accidents, and insulations which withstand these surges. Charging resistance on aluminum arresters is chosen to make surges harmless, and the charging resistance gives great immunity from damage to the arrester itself by any accidental and temporary local condition in the arrester. In conclusion, the aluminum-cell arrester may justly be regarded as a standardized electrical device founded on solid fundamental principles.

ALTHOUGH the aluminum-cell lightning arrester is now many years old in practise, there is available in the TRANSACTIONS of the Institute very little definite scientific information on this subject. It has seemed preferable to produce certain results rather than describe beforehand how such results were to be obtained. The practise of the aluminum arrester has now settled down to definite sets of conditions, and it is the object of this paper to consider standard conditions and open up the subject to discussion. Aluminum lightning arresters will be treated in general on points that may seem debatable. No detailed description of apparatus will be given herein.

The question is often asked—Will certain types of arresters be superseded? In very few cases has it been possible to give a definite answer to such a question, owing to incomplete knowledge of cloud lightning phenomena. It has been possible to say that if future investigations of cloud lightning prove that every lightning stroke is of high frequency and steep wave front,

certain changes would come about under these conditions; it would be possible to prophesy, with considerable confidence, that many types of lightning arresters now in use would disappear. The natural growth of protection would be along the line of various types of high-frequency absorbers.

If, on the other hand, it should be shown that lightning is always of low frequency, and gives the surge a sloping wave front, then again, it would be fairly safe to prophesy the contrary—that very few of the lightning arresters now in use would disappear, and that probably no other devices would take their place.

Recent investigations of lightning phenomena have confirmed our views that cloud lightning has wave fronts of various degrees of steepness, and without question some of the lightning strokes are not high-frequency effects but are of the nature of simple impulses. The writer's recent experiences along this line have been gained by indirect methods. Lightning arresters have been put out which were sensitive to very high frequencies, and at high frequencies had very good protective qualities; but at very low frequencies their spark potentials were greater than at high frequency. Other arresters equally sensitive to both high and low frequencies have been installed in the same locality. This experience has indicated that many of the strokes are of low frequency. The most valuable and practical investigation of lightning arresters that has yet been made on a large scale has been carried on by Mr. D. W. Roper, and no doubt these results, which are incomplete at the present time, will be made available at some later date. More direct measurements of lightning taken with an oscillograph have been made by Mr. L. A. De Blois. These, I believe, are the most valuable direct tests that have been made in many years. I am personally indebted to both Mr. Roper and Mr. De Blois for information on their researches, and I understand that their valuable work will be presented to the Institute at some future meeting.*

In the development of the present standard arresters our knowledge of lightning gave us no alternative but to assume that lightning had all the characteristic qualities of the various surges that could be produced in the laboratory. For example, we have assumed:

That the frequency might be from zero to 5,000,000 cycles per second.

*See paper by L. A. DeBlois, *Some Investigations on Lightning Protection for Buildings*, page 519, this volume.

That the wave front might be either vertical or angular.

That the quantity of electricity was both large and small.

We have known from our earliest investigations that several strokes came in succession. It was also necessary to take into account the effects of the energy from the generator which followed the lightning discharges. In this way we have endeavored to be prepared to meet any new information that might come concerning lightning strokes. Naturally, all these different factors could not be given equal weight in the design, and therefore, as more definite information regarding the nature of lightning is obtained, the designs will be strengthened in the features that these investigations may show are weak. It is a matter of increasing the ultimate efficiency by a small percentage.

The direct-current aluminum arrester is practically ideal from the standpoint of protection. It has no series gap and therefrom it gains two valuable characteristics: the first of these is the elimination of any dielectric spark lag; and the second is the absorption of high frequencies which have a less potential than the circuit potential. Commenting on these two conditions, the dielectric spark lag, although it is ever so small, is still appreciable as compared with the time of movement of a surge along overhead lines. A surge will travel a mile (1.6093 km.) in about five millionths of a second. If the surge is a mile long, and the dielectric spark lag is five millionths of a second, such a surge will have passed along the line without starting a spark across the gap. The only means of discharging such a surge would be by introducing a choke coil in its path and thus delaying its movement sufficiently to allow the spark gap to become ionized. Since the spark gap of the a-c. aluminum arrester has a setting which may be only 25 per cent above the line potential, high-frequency surges can be deflected into the arresters if the potential either of the surge or the superposed value on the 60-cycle potential reaches the spark value. If the generated potential happens to be zero at the instant, it is evident that the surge itself must have a value 25 per cent above normal in order to cause the arrester gap to spark. The d-c. aluminum arrester, by its direct connection, is able to pick up surges of all frequencies and all potentials immediately on their arrival at the terminals of the arrester.

The practical demonstration of the protection afforded by these d-c. aluminum arresters confirms the theoretical work and experimental tests made on the cells. The discharge rate at

double potential is more than a million times as great as the leakage current at normal potential.

From a practical standpoint, the cost of such arresters must be considered. While the cost and upkeep of the d-c. aluminum arrester is greater than for the older types using gaps and series resistances, still the aluminum arrester is the more economical one to use. The higher protection given by the cells would justify some increase in expense on account of the better service that can be maintained. But, as a matter of fact, the actual expenditure for the protection as a whole becomes less, due to the fact that good protection on the cars makes a less demand for the use of arresters along the trolley line. The saving in the cost of line arresters will more than compensate for the extra cost and upkeep of the aluminum arrester. Moreover, even with the very best types of gap arresters on trolley cars and trolley lines it is impossible in lightning-infested districts to maintain the car service. The percentage of protection from the gap type of arresters is not high enough even when the best arrangement of wiring and choke coils is used in conjunction with the arresters.

There is one further function of the d-c. aluminum arrester that has considerable value, and that is the absorption of electromagnetic surges coming from the interruption of accidental short circuits on the trolley line. Such high potential across loaded motors has a tendency to cause flashing around the commutators. If the flashing around the commutator is caused by the excess potential, then the d-c. aluminum arrester will relieve the trouble.

Answering, then, the frequently asked question—Will the d-c. aluminum arrester be superseded?—the answer is, in principle, no. Improvement in details may be made, and there may be discovered some new and better substance than the aluminum film, but none is yet known. Any degree of protection that is desired at its terminals can be obtained by the use of this arrester. An improvement in the length of life of the arrester is desirable, but this will not be superseding it. The discovery of some new substance that will give the same electric valve effect at a definite voltage only slightly above the operating voltage would be no particular improvement, unless perhaps it might be something that would not deteriorate when left disconnected from the circuit.

Turning next to the a-c. aluminum arrester, it was found impracticable to maintain simplicity and long life in the arrester

and at the same time keep the arrester directly connected to the circuits. For this reason the horn gap was introduced in series with the aluminum cells. Since the hydroxide films on the aluminum plates gradually dissolve in the electrolyte it becomes necessary to introduce a method of charging the cells. The simplest method was first tried: it consisted of bringing the horns near each other and reducing the gap to a very small value. Many trial installations were made under these conditions and no bad effects were obtained. When the number of arresters in use ran up into the thousands, then an occasional trouble resulted from the rush of current into the aluminum cells.

The aluminum cells are condensers and as such will take initially a considerable rush of current. Furthermore, the dissolution of the aluminum films required a considerable quantity of electricity from the line to reform them. Where the films had been subjected to unusual dissolutions either by standing in hot electrolyte, resulting from atmospheric temperature or long periods of discharging, or from neglect to charge, the current rush into the aluminum cells became a serious menace, mostly to the arrester itself. Since there is no external indication of a bad condition of the aluminum cells, even an expert would be unable to know if it were permissible to close the charging gap of the arresters. This led naturally to the use of charging resistances in series during the ten seconds a day needed to charge the arrester. The charging resistance is an added expense and an added complication. But the added complication is relatively small, and the all-around increase in the safety of the arrester is great enough to justify both the cost and complication, from the user's standpoint.

The subject of possible surges accompanying the charging of aluminum arresters is one far more pertinent in an article written for foreign readers than in one for American engineers. The foreign operators seem to have had misfortunes with their arresters that have not been duplicated in America. The reason for this might be attributed to a number of different causes, depending upon the country and the localities. These reasons might be enumerated as methods and care in manufacture, the lack of definite and emphatic instructions to operators, poor distribution of insulation in transformer coils, and difficult situations caused by any one of several factors, such as, for example,—high temperature, bad regulation of the line, and insufficient care after an arrester had been called on to discharge continuously during an accidental ground.

The general results from any one or more of the foregoing enumerated factors may be classified under two heads: first, a short circuit in the arrester and consequent interruption on the line; and second, surges set up on the line without any damage to the arrester. Nearly all these conditions can be rendered harmless by the use of charging resistances. The one important exception is the matter of bad regulation of a line in which the power voltage is allowed to rise to values above the spark potential of the arrester. Under these conditions of discharge the arrester is no longer being used as such, but rather as a rheostat to absorb the generated power. The arresters cannot, at any reasonable expense, be designed to act as rheostats. While it might, in special cases, be possible to develop arresters which would withstand these conditions, the better solution of the problem is to improve the regulation. If care in manufacturing the aluminum plates and the electrolyte is not taken, and the installation made free of dirt and impurities in the electrolyte, more or less deteriorated conditions will exist throughout the life of the arrester. Certain kinds of impurities have a strong destructive effect on the films. A condition of unusually high operating temperature may call for an electrolyte especially adapted to high temperatures, or it may simply be taken care of by charging two or more times a day. Dissolution of the film from standing in hot electrolyte after the arrester has discharged continuously for a number of minutes can cause no trouble if a reasonable charging resistance is used, as the series resistance limits the current to a value which will not damage the arrester. With the exception, then, of high generator potentials from bad regulation of voltage, there is no difficult problem connected with the use of aluminum arresters.

A discussion of the aluminum arresters would not be complete without some reference to the possible surges that may be set up by the charging of the arrester. Surges on an electrical system may be considered in a list of ascending degrees of severity. Turning on an incandescent lamp sets up an electric wave on the system by calling on the generator for more power. A surge of this kind is of the third order of importance, and therefore, entirely negligible. It is well known that any spark or arc in the circuit containing inductance and capacity tends to set up oscillations, but if the resistance in series is equal to, or greater than, the critical resistance, oscillations will be prevented.

It is common practise to-day to open and close circuits which

contain inductance and capacity without introducing in series a resistance to absorb the transient surges that are thereby set up. It is also common practise to-day to use circuit breakers to open accidental short circuits in which there is a high value of surge energy, and sometimes high voltages.

Going still a step further, every circuit is subject to accidental arcing grounds, which produce continually on the circuit dangerous surges which are often but slightly damped. It is difficult to protect apparatus from these most severe conditions of surges. In general, however, apparatus is built to withstand severe treatment, and there is but a small percentage of loss. Therefore, when we come to consider surges on the system we should take into account the conditions of insulation in relation to the severity of the surge.

In all these graded degrees of severity of surges, where should the aluminum arrester be placed? If there were a demand for it, the arrester could be placed in the list next to the negligible surge of connecting an incandescent lamp to the circuit, and this could be accomplished by using graded resistance in charging. In view of the insulation of the apparatus that is needed for the usual condition of operation and to withstand the inevitable accidents which cause severe surges from time to time, the use of graded charging resistance would be a needless and inconsistent precaution. It is sufficient to say that it could be done if it were desired.

What is actually done is more reasonable. A relatively large value of resistance is used in the charging circuit, limiting the current to a range of 5 to 15 amperes. Charging resistances are an intrinsic part of aluminum arresters as now manufactured. Strong recommendations have been made to operators to add them to their older arresters. A characteristic answer is to the effect that "our arresters have been charged through a gap for six years without trouble, and we are satisfied." The change is brought about not by reason of surges, unless they cause telephone interference, but rather on the ground that the arrester is made more immune from damage to itself.

In foreign countries, with their water jets and resistance types of arresters, the controversy over arresters still waxes as warm as it did here in the formative period some eight or ten years ago. The following argument is advanced against the aluminum arresters: admitting that the charging resistance does away with the surges, what about the heavy strokes which cannot pass

through the charging resistance and therefore jump the main gap directly into the cells to ground? To anyone familiar with the practise here up to 1913 an answer is unnecessary. If this discharge path were a menace, devices could be used to mitigate it. The nature of the menace can be understood by a review of the past practise. There are several thousand aluminum arresters in use that have been charged through a gap without series resistance. Good practise now condemns the method, but there it is. Ten seconds' charge a day produces over a thousand makes and breaks. There would therefore be more than a million total made per day and more than a billion in a few years. Judging by the rare cases of trouble in this vast number it cannot be much of a risk to allow a few discharges per year to pass directly to ground through the aluminum cells, especially in face of the fact that such a surge is so dangerously large that it cannot be relieved through the resistance, and therefore the surge itself is an undoubted menace to the insulation as it runs wild over the electrical system at 186,000 miles per second.

The status of the aluminum arrester, therefore, is that of a device founded on the solid principle of a safety valve. It has definite limits of maximum current discharge rate and of energy absorption, beyond which damage to the arrester will result. In this respect it is no different from other standard apparatus. Years of experience have demonstrated that these limits are far above the usual demands of practise, but naturally it is not impossible to pass them. The flexibility to meet special conditions is great. Film area, internal resistance, relative gap settings, external resistance—all are readily adjustable to the demands which may possibly come as our knowledge of lightning and other surge phenomena is increased.

DISCUSSION ON "THE PRESENT STATUS OF ALUMINUM-CELL LIGHTNING ARRESTERS" (CREIGHTON), NEW YORK, FEBRUARY 27, 1914.

V. Karapetoff: I would like to ask Dr. Creighton whether he has had any experience with the glass condensers and valves made in Switzerland and known there as the Moscicki condensers and Giles valves.

F. W. Peek, Jr.: It is some time since I have been actively connected with work on the aluminum lightning arrester. A number of years ago I had the good fortune to be able to make a study of lightning and the operation of the aluminum arrester on a practical line in Colorado. We had the co-operation of one of the operating companies in the experiments on this system, which was high up in the mountains. It was a 17,000-volt network and a 50,000-volt main transmission, with a 50,000-volt idle line upon which to experiment. Various forms of lightning arresters had been tried by this company without success. It was practically impossible to continue operation during a storm. At this time the aluminum arrester was very new and we did not intend to make use of it as a practical protection; our idea was to make a study of lightning itself. However, in an attempt to improve operating conditions it was decided to install a few aluminum arresters. These arresters could not be obtained from the factory at that time. It was a very difficult country to get into. A sufficient number of aluminum cones was obtained, however; containing tanks were built in the mountains, and the electrolyte was compounded from chemicals bought at a local drug store. An arrester was thus built up and put into operation, and it did very good service. It was decided to install a few more. At a later period in the season these were obtained from the factory and were distributed to various substations. During the latter part of that season there were very severe storms and very little trouble. Many improvements have since been made in the arrester, notably in the electrolyte and in the addition of charging resistance.

The aluminum arrester is the only arrester at present that can take care of a condition of high-energy lightning discharges of moderately steep wave front or moderate frequency. This is often the only condition; generally the prevailing one that must be met. Good protection is thus obtained in the majority of cases, with an occasional miss during the season. There are certain conditions, generally in the minority, but which occasionally on a few systems are the prevailing ones, which no arrester with a gap can, unaided, satisfactorily take care of. These conditions are:

1. Lightning impulses of exceedingly steep wave front and high voltage.
2. Impressed high frequency of a voltage insufficient to discharge the gap.

In condition (1), the dielectric breakdown time lag of the gap may prevent discharge of the arrester before discharge takes place at some weak point in the system.

In condition (2), discharge does not take place at the gap because the voltage is not high enough, but the oscillations may build up high voltage internally in an apparatus containing inductance and capacity.

Both conditions (1) and (2)—which may be considered as more or less special—may be taken care of by the proper arrangement of resistance, inductance and capacity.

Good engineering requires as high system insulation as is economically possible, with the weak point at the lightning arrester.

L. C. Nicholson: Electrolytic lightning arresters are coming to be very widely used, and I think by this time they are recognized as the standard type of station arrester.

Frequently the question is asked—Are they efficient? Are they necessary? We operating people reply by saying, "Yes, they are necessary, if you think so," the result being that most of us are afraid to leave them off. As far as I am acquainted with the operating results of this type of arrester, there is seldom any apparatus damaged when protected by such an arrester, and I will also say that when the apparatus is not protected by such an arrester, there is very seldom any damage. So it appears that the arrester is all right. Except on extremely highly insulated transmission lines, damage to high-tension apparatus in the station by lightning is rare.

Usually lightning effects are so localized that the line has its own trouble and keeps it. I am acquainted with an installation which uses a pretty wide gap between the line conductor and earth, say 100 per cent over voltage, which discharges once a year, and which seems to be about all the protection that the station apparatus really needs, judging from the fact that no station apparatus has been punctured. I am acquainted with other stations which have electrolytic lightning arresters and which are not troubled by lightning and I am acquainted with some which have electrolytic lightning arresters and are troubled by lightning, so that it is very much of a question as to whether lightning will or will not do damage under certain conditions of station protection.

At least, the aluminum electrolytic lightning arresters have been developed to a point where there is no longer any danger of their exploding or giving any trouble on their own account if properly cared for, and the usual station attendant, with sufficient instructions, can properly care for the arresters and keep them in proper service. I feel sure that the addition of charging resistance has been of great benefit to the operation of this arrester.

The pity is that these arresters cannot extend their influence beyond half a mile from the station. In most cases the trouble is beyond that point.

C. O. Mailloux: Reference has been made to the character of the "front" of the wave which strikes a line or a portion of circuit protected by lightning arresters. It is known that the vertical front of a wave may be flattened out and sharpened to a point, so to speak, in passing through a reactance. It would seem therefore, as if one might expect that the character of the wave-front would depend somewhat upon the distance from the apparatus at which the lightning strikes the line. One might expect that the lightning striking the line very close to the lightning arresters would produce a current-wave having a squarer, straighter front, a more vertical one, than if it struck at some distance, owing to the difference in line-reactance. It may be that in most cases this would not make much difference. In any case, it should be possible to alter the wave-front, to some extent, by the introduction of artificial reactance.

C. P. Steinmetz: I wish to refer to only a few features. Setting aside failures of insulation due to weakness or poor design of bushings, insulators, etc., it occasionally happens that even a good lightning arrester fails to protect coils of transformers. The explanation of this is a feature which I have endeavored to make clear in my paper. These failures mean merely that when we speak of lightning we do not know the nature of the surge, and it is necessary to make such studies as will determine it—why at times the surges cause damage and other times they do not.

The aluminum arrester, with a gap in series, may protect against any surge which reaches the aluminum cells. Any disturbance of a voltage less than that which will jump the gap and thus reach the aluminum cells naturally cannot be absorbed by the aluminum cells. Therefore, if we have a high-frequency oscillation of a voltage sufficiently low not to jump the spark gap and incidentally sufficiently low not to do any damage to the line, such a voltage may not be able to do harm to the insulation from line to ground, but when massing of the surge occurs in a few turns of reactance, such as a single coil of a transformer, it may do very great damage, because, while the apparatus is designed to stand the line voltage, it is not designed to stand half the line voltage across say one-hundredth or one-thirtieth of the circuit. The main trouble due to high frequency comes from the local massing of voltage across the reactance.

In speaking of high frequency we may refer to various different effects, and we also usually mean a thing which is not high frequency at all, is not even oscillation—it is steep wave front. A steep wave front, to some extent, causes the same trouble, namely the same massing of voltage, but in other respects it is very different. Some types of protective devices, like the multi-gap arrester, are very sensitive to high frequency, and will discharge high-frequency surges of voltages much less than the operating voltage, but they are not sensitive to steep wave front and may allow steady voltages of steep wave front to rise far above the circuit voltage without discharging.

Another illustration of this difference is given by the application of a condenser. Where there is very high frequency, a condenser shunted from line to ground may bypass or practically short-circuit the high frequency, but where there is a unidirectional wave the condenser will take a charge and thereafter offers no obstruction to the rise in voltage.

We must realize that electrostatic capacity is not a lightning-protective device—is not by itself a protection. A capacity from line to ground merely is a thing which will charge and store the energy. The storage is transient and the energy in the condenser must be returned to the circuit. Thus the condenser in the line will have no effect at all on steady voltage, or on low frequency. The favorable action the condenser can have is apparently to short-circuit disturbances of relatively high frequency.

Such disturbances, in my opinion, are rare, if they exist at all on transmission lines. For the reason that the capacity of the transmission line is so large, compared with the capacity which can economically be provided for in a condenser, any small condenser which can be shunted across the lines at the station would not be capable of appreciably short-circuiting the surge. Thus the high-voltage and the high-frequency disturbances of such volume and such current as can come in over the line are not cared for by any condenser of practicable size.

It is different when the surge comes from the other direction—that is, where the high-frequency disturbance comes from the station. In the transformer, as in the line, the circuits have distributed inductance and capacity, but in the transformers the inductance is very much greater, and the capacity very much less than in the line, and therefore the ratio of voltage to current of the disturbance is very much greater. In other words, capacity has an appreciable effect on a traveling wave, when the capacity is shunted around the high-potential windings of the transformer.

The value of capacity in protective devices lies in the fact that it is a barrier against the passage of current at machine frequency without being a barrier to the passage of surge currents which are inherently of high frequency. Under these conditions it is possible to use a resistance of low value in series with the condenser without absorbing any appreciable power at machine frequency. At high frequency, however, the power factor approaches unity and the maximum possible energy of the surges is absorbed. Thus it is seen that it is not the capacity in itself that is protective, as the voltage absorbed by the capacity at high frequency is negligible, but it is the capacity allowing a properly proportioned resistance to give protection by absorbing the energy of the wave.

This is the condition in the aluminum electrolytic cells, where there is a high equivalent resistance in series with the natural capacity of the cells.

The capacity of the aluminum cell gives a moderate power

factor at average machine frequency, but when there is applied a frequency of 100,000 cycles, the power factor of the aluminum cell is practically unity, that is to say, practically all the high-frequency current which goes through the cell is dissipated as energy and does not store itself as energy to be turned back into the circuit, as would be done by a simple capacity.

I believe that the action of the aluminum cell can best be represented by calling it a counter-electromotive-force device. It acts as a counter-electromotive-force shunt between circuit and ground after the voltage has reached a definite value. Up to this definite value, *i. e.*, discharge voltage of the spark gap, it is an open circuit, and beyond that voltage it is a closed circuit. In the closed circuit condition it has about the same effect as if in a d-c. system you shunt a storage battery from the trolley wire to the ground. If you connect between the trolley wire and ground a 600-volt storage battery, then no lightning or any other disturbance will be able to raise the voltage of that trolley line appreciably above 600 volts, because any attempt to raise the voltage would merely cause a discharge through the storage battery. The discharge rate depends on the internal resistance and voltage above the polarization of the storage battery; so it is in the aluminum cell, where the discharge rate depends on the voltage in excess of the polarization value and on the internal resistance of the cell, which, as we all know, is very low.

Now, as to the possible danger from the use of the aluminum cell, which has been especially discussed by those who have had very little practical experience with it—that is, the question whether it may produce high-frequency oscillation. One argument against the production of high frequency I have mentioned already: the power factor of the aluminum cell is unity and it has no capacity effect at high frequency, but it gives a thoroughly damped circuit of a resistance which prevents oscillations. But from another view-point, the best comparison is that given by Professor Creighton—it is a safety valve from line to ground, of very high discharge rate.

We would not think of installing a high-pressure steam boiler without a safety valve, and still, many of us know that every once in a while you hear that a safety valve is really a source of danger, because if a steam boiler is superheated, and water is low, and just at the point where it is near blowing up, and if the safety valve operates, then the sudden shock of the safety valve opening may set off the explosion. But that is no reason for saying that it is unsafe to use safety valves and that all the steam boilers should be operated without them. It is exactly the same case with the aluminum cell or any protective device. If you protect the system against over-voltage, and if the energy back of the over-voltage is very large, it means that to relieve the over-voltage strain we have to provide a device with a high discharge rate, and the sudden coming into play of that high discharge rate, which is required to relieve the strain, means a sudden

shock to the system, and if you are near the breakdown point, that very shock may cause a breakdown.

But it has been said that it is not necessary to have a free discharge, and that a resistance may be inserted between line and ground—a critical discharge resistance which will gradually relieve the voltage without oscillations. That is very nice. By so doing the shock is removed only by keeping the excess voltage on the line and the apparatus for a considerable time, and for the time, in fact, that it takes to discharge, and since the disruptive strength depends on the time of applied voltage we wish to relieve, we must conclude that we are between two extremes. We have a condition of excessive voltage brought on by lightning or other disturbances. This voltage is dangerous, is certain to destroy apparatus and line if it stays long enough. We may gradually relieve, or we may suddenly relieve, but since the voltage is certain to destroy, the most effective way is to relieve it as quickly as we can, even if in the extreme case the very suddenness of the relief may accelerate the damage, which is, however, very improbable. I do not know of any instance where this has occurred, and I think the point raised in this connection is more theoretical than actual.

There is one point I want to mention about steepness of wave front. The steepness of wave front depends on the distance of the place from the point where the wave originates. Theoretically, if you calculate transient phenomena of the line, you will find, by an equation, that the wave shape is so steady that the wave starting as a steep wave front retains its steep front all over the line. Practical experience shows that this is not so, and that is one of the various points where theory and calculation do not agree, or where, in our theory, we make an assumption which we find is not warranted—that is, we assume the effective resistance and effective conductance to be constant, independent of the frequency, while in reality every decrement increases with increase in frequency.

If you assume that the effective resistance of the line is a function of the frequency, increasing with increasing frequency, then you would find in the equations (if the equation did not come out so complicated) which so far have been beyond the mathematical skill brought to bear upon them, that the steepness of the wave form decreases with increasing distance traveled by the wave.

But while the equations have not yet been solved to give the values of the increase in resistance of the line, experimental evidence is available. There were some very interesting tests, for instance, made by Mr. Faccioli some years ago, on the wave produced by opening the high-tension switch in a 90,000-volt circuit. In that case, at and near the point of opening of the switch, the steepness of the wave front was such as to give, across a choke coil the inductance of which was equivalent to 50 feet of line, a potential difference of 30,000 volts, but the same size of coil on the same line at 20 miles distance,

gave no appreciable steepness of wave—that is to say, in the switching test there was no discharge on the spark-gap shunted around this small reactance. Within 20 miles of travel the wave front changed from an extremely steep one to a very flat one. This is the experimental evidence of the high resistance offered by the copper line wire when the potential is suddenly applied.

E. E. F. Creighton: I feel that there is no need to say anything further about the Moscicki condenser, in answer to Dr. Karapetoff's question, as Dr. Steinmetz has already covered the subject.

I am glad that Mr. Nicholson has thrown a little spice into the controversy by speaking of the cases where apparatus was not damaged and the arresters were installed, and also cases where the apparatus was not damaged and the arresters were not installed. Each one of us speaks from his experience, especially his own personal experience, and Mr. Nicholson, I take it, is speaking from his. If I may be permitted, I would like to analyze some of the conditions under which he has been operating and then contrast them with some other experiences which have been gained on other transmission lines where the conditions are different.

On that particular system to which Mr. Nicholson referred there was, a few years ago, an almost insurmountable problem of keeping the lines operating during thunderstorms. I have the greatest admiration for the way in which Mr. Nicholson has attacked this problem and obtained a workable solution. The point of it was that the insulators on the line had not only less factor of safety than they needed, but they punctured, and where every insulator on the line is a lightning arrester it is quite true there is less need of lightning arresters in the station. Under these conditions the principal need of a lightning arrester in the station is where the lightning happens to strike in the neighborhood, and that, I think, corresponds to Mr. Nicholson's remark that it is too bad the lightning arresters cannot reach out more than a half-mile from the station. I should say that it is too bad the lightning is so terribly concentrated at points on the line. That represents, to my mind, the experience gained in that particular case.

On two other lines I know of, where the insulation of the lines was made for operation at 100,000 volts and the operating voltage was only 20,000 and 40,000 volts, the results were quite different. Since the factor of safety of the insulators was about 10, they were not functioning as lightning arresters or protectors for the apparatus, and consequently every lightning stroke that appeared on the line came with horrible impetus into the station. Switch bushings, transformer bushings, and other insulation that had withstood the conditions of other circuits, immediately began to break down from flash-over or by puncture. Lightning arresters of the best type were then required.

This is a condition that is gradually growing all over the country. Everywhere operators find that insulation on the line is an important factor, and are increasing the factor of safety in the line insulators. Personally, I would never use a factor less than three times normal potential, preferably still higher. The extra investment in insulators is worth while. This ultimately necessary practise will increase the need of lightning arresters.

The lightning arrester in itself is not a surge protector, but an over-potential protector. The gap setting is 25 per cent above normal operating voltage, and the arrester will operate as a surge protector only after the gap sparks and connects the aluminum cells directly to the line. I am somewhat disappointed that there has not been more adverse criticism, as our foreign friends are finding a great many things to say. I feel that any criticism or any failure of the aluminum arrester to protect the circuit can be explained by some weak local condition, or, otherwise, the design of the arrester can be easily modified to meet new conditions. As Dr. Steinmetz has so well emphasized today, the great need at the present time is more definite information. A few years ago it was a very common thing to have bushings fail on transformers and switches, but today, due to the presence of the aluminum lightning arrester, these faults have almost entirely disappeared. Those that have not disappeared I hope to be able to give a reason for, at some not far distant time, as a result of the study of porcelain insulators at high frequencies. Porcelain insulators and bushings have a different strength at 60 cycles on which they are usually tested, from their strength at very high frequencies, such as 200,000 cycles per second—or its equivalent, expressed as steepness of wave front.

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TRAFFIC STUDIES IN AUTOMATIC-SWITCHBOARD TELEPHONE SYSTEMS

BY W. LEE CAMPBELL

ABSTRACT OF PAPER

The paper describes a telephone traffic recording machine by means of which not only the number of calls for a given period, but also the average duration of each call, is mechanically registered on a moving tape. The observations recorded here were taken on an automatic telephone system. The graphical record shows the exact duration of each connection, the number of connections made during a given interval, and the number of simultaneous connections in service at each instant. By means of these records it is possible to study the relative efficiency of small and large trunk groups, the average holding time of calls, and these observations permit the switches and trunks to be so arranged that the calls will be evenly distributed among the trunks in each group.

THE WORD "traffic" as used in telephone practise applies to the volume of calls which a system handles. To measure traffic it is necessary to know not only the number of calls for a given period or interval of time, but also the average duration of each connection or call. A knowledge of traffic, and the laws governing it, is essential to the proper design and operation of either an automatic or a manual system.

OBSERVATIONS OF TRAFFIC

In well-managed manual switchboard central offices it is customary to study traffic conditions by taking peg counts and plug counts. A peg count is a count of all connections made during a definite time interval by each of the operators. A plug count is a count at a definite instant of all plugs in use. In addition to these, stop-watch observations must be made to determine the average length of connection, or "trunk holding time", as it is often called. Where the trunk holding time is known, a good way to take both a peg count and a plug count has been to use a recording ammeter connected into a circuit supplying energy to some or all of the relays; then knowing the average ampere-hours consumed by each connection, it is a

comparatively simple matter to determine from the ammeter records both the total number of connections made and the maximum number of connections existing at the busiest instant. The latter is an especially important matter because it determines the amount of connecting equipment required to take care of the peak load.

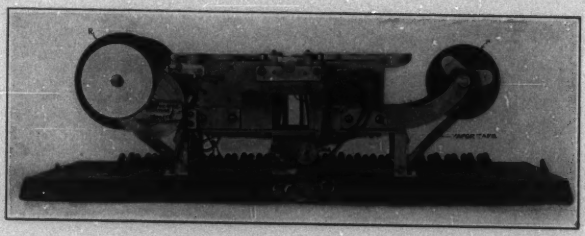
It is very difficult, if not impossible, to secure a very accurate peg count or plug count. Operators frequently make mistakes in registering calls during a peg count and observers make mistakes in counting plugs; mistakes are also made in distinguishing between cord circuits actually in use and those which are apparently in service but really idle, because the conversation of the parties using them has been completed.

In automatic central offices, counts corresponding to peg counts are occasionally taken by counting the operating switches as they complete connections. Calls are also counted by the use of a meter on each trunk; these are generally installed by connecting the release magnets of 2nd or 3rd selector switches on each section of the switchboard to a separate busbar, in series with which is a ½-ohm relay which operates each time a switch releases, and closes a circuit through a meter. Counts similar to plug counts have been taken by counting all of the like trunking switches in operated position at given times.

Traffic-Recording Machine

All of these methods of measuring traffic have their disadvantages and it is believed, therefore, that telephone traffic engineers and telephone engineers in general will be interested in a new recording device and some of the results secured by its use during the past year in making traffic studies in automatic switchboard plants, on a somewhat elaborate scale. The special feature aimed at in this machine was to secure a graphical record which would show the exact duration of each connection, the number of connections made during a given interval and the number of bona-fide simultaneous connections in service at each instant.

The machine as devised consists of a mechanism for passing a strip of paper about 6 in. (15.2 cm.) wide over an inked ribbon and onto a receiving roll at definite rate of speed, with a number of markers (40 in all) arranged side by side over the paper, so that when any marker is pressed against the paper the inked ribbon leaves a corresponding line on the paper. Each marker



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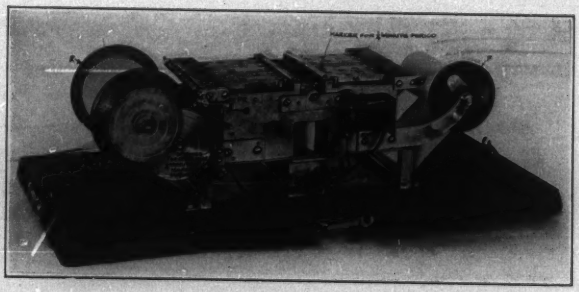

[CAMPBELL]

FIG. 1

is provided with an armature and an electromagnet for operating it; the latter is electrically connected to the mechanism associated with one automatic switchboard trunk in such a way that whenever that trunk is occupied by a call, the potential established on the trunk for guarding purposes serves also to cause current to flow through the electromagnet and energize it as long as the connection lasts.

Two views of this machine are shown in Fig. 1. *F* is the roll feeding paper to the machine; *R* is the receiving roll; *M* are the markers; *V* is a pendulum vibrator tuned to run at a fixed speed, so as to make and break at regular intervals the circuit through the electromagnet operating the step-by-step pawl and ratchet movement *PR*, which turns the receiving roll and thus draws the paper through the machine; *R M* is a device for moving the ribbon at intervals so that the portion immediately under the markers will always be sufficiently inked. A skeleton view of the mechanism with its associated circuits is shown in Fig. 2.

Sample Observations with Machine

A section of the paper tape taken from the machine and covering a record of calls during a busy half-hour on a set of trunks in the business central office of a city in Michigan is shown in Fig. 3.

One especially interesting feature is the remarkably short period of time which occurred in many instances between the release of a trunk and its seizure for another connection. This is of material aid in promoting trunk efficiency, and is due to the automatic switchboard. As indicated in the figure, the vertical lines mark $\frac{1}{4}$-min. periods. It was found that by means of a chartometer, it was not a difficult matter to sum up the lengths of the lines on each tape, so that the average length of call might be obtained; and it is apparent that a curve may be very readily made from this sheet, which will show the number of simultaneous connections at each instant, as the curves in Fig. 4. In fact, any traffic data desired may be secured from the tape.

The upper curves *A* and *B*, in Fig. 4, are taken respectively from the upper and lower halves of the same tape, from whose totals the lower curve was constructed.

Trunk Efficiency

The writer's purpose in presenting these curves is to give a graphical illustration of the relative efficiency of small and large

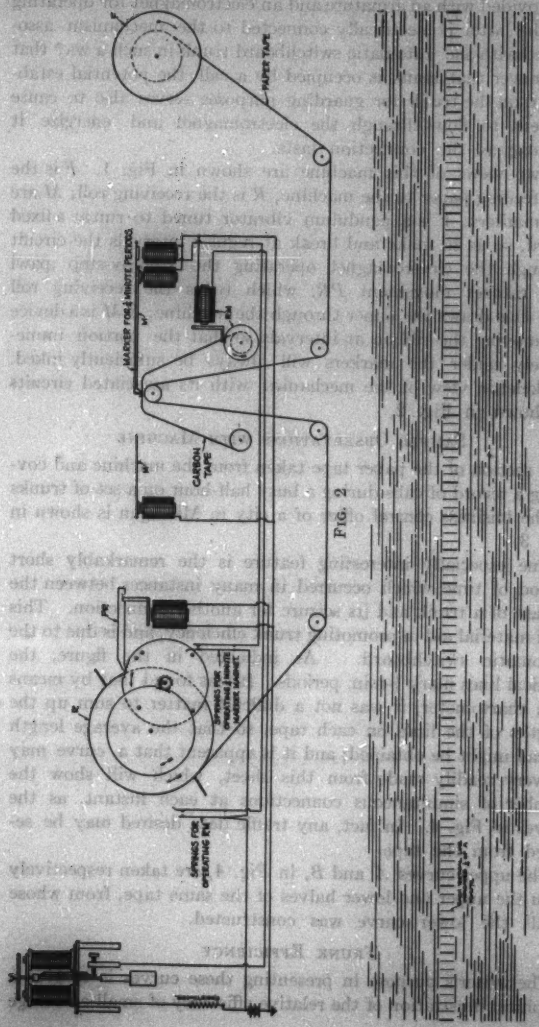
PAPER TAPE
MARKER FOR 5 MINUTE PERIODS
CARBON TAPE
SPRINGS FOR OPERATING PEN
SPRINGS FOR OPERATING 5 MINUTE MARKER MAGNET
SECTION FROM TAPE OF TRAFFIC RECORDING MACHINE.

FIG. 2

FIG. 3

trunk groups, by noting the fact that while in the group *A* the maximum number of simultaneous connections is 18 and in group *B* the maximum number is 18, the maximum number in a combination of the two is not 18 plus 18, but 32. This is merely an illustration of the law of increase in efficiency of trunks as the size of the group increases which has been well known to telephone engineers for years; but the author is not aware of any other device which makes it possible to study the working of the law so satisfactorily. The fact that the greater efficiency of large trunk groups is due to a smaller ratio of peak load to average load is very clearly demonstrated by the curves

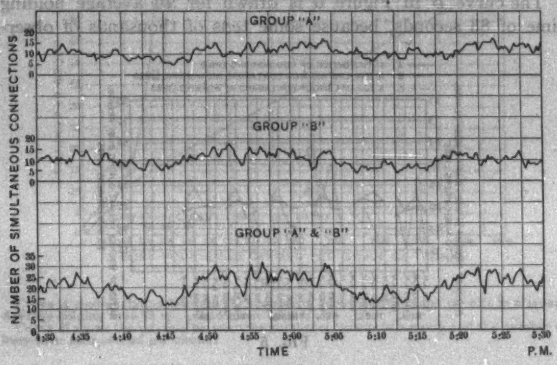

FIG. 4

in Fig. 5, which were constructed from data secured in an office of 7950 lines, by making simultaneous observations during the busy period of each of six working days, on the number of connections in service at given instants in each 100-line section of the entire plant. Note the much greater variation (Fig. 5) in the percentage of connections in the average 100-line group than in the 1000-line section, and the very small variation in the load of the entire plant.

It is customary to define the peak load in terms of the average load or the total busy-hour load. One of the curves, *A* in Fig. 6, shows, for calls of 83 seconds duration, the relation between the total busy-hour load and the peak load, in automatic

switchboards; or, in other words, the number of trunks needed at the peak instant for busy-hour loads of various sizes. This curve follows the formula:

$$\text{Number of trunks} = T\ C + 3.785\ (1-T)\ \sqrt[3]{C\,T} \qquad (1)$$

For call lengths of less than 130 sec. this formula may be written in the simplified form:

$$\text{Number of trunks} = T\ C + 3.7\ \sqrt[3]{T\ C} \qquad (2)$$

T is the average holding time in hours, and C is the number of busy-hour calls.

Average Holding Time

The curve B in Figure 6 is drawn for an average holding time of 83 seconds, because some tens of thousands of obser-

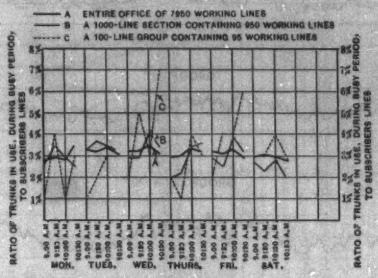

Fig. 5

vations made in different automatic plants show this to be slightly above the average duration of connection. The 83-sec. standard is divided as follows:

Setting up of automatic connection	6	sec.
Waiting for called party to respond	9.5	"
Conversation	66.5	"
Release of connection	1	"
Total	83	sec.

Call lengths vary greatly in different offices. For example, in one of the cities in which studies were made with the traffic recording machine, it was found that while the average length of calls for the entire system was 81.25 sec., it was 130 sec. on the trunks to an outlying residence office and 100 sec. on trunks to

manual private-branch exchanges; but observations made on inter-communicating calls in automatic private-branch exchanges have, in a number of instances, shown an average call length as low as 43 sec.

In connection with the studies of average call length, it was found that in approximately 12 per cent of the calls the calling party received the busy signal; and 16 per cent received no response from the called party, either because he was beyond the reach of the telephone, or did not answer the signal before the calling party disconnected.

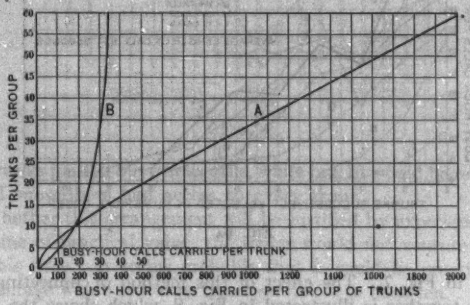

FIG. 6

Curve *A* shows relation between the number of busy-hour calls and circuits in a group. Average holding time 83 sec. Automatic system.

Curve *B* shows the relation between the number of circuits in a group and the number of busy-hour calls carried per circuit.

TRUNK GROUPING

It is common practise in automatic switchboard systems to arrange the switches and the trunks so that the calls will be evenly distributed among the trunks in each group. This is done to distribute the wear on the trunking switches, to ensure all the switches enough operation to keep them in good working order and to reduce the risk of two parties seizing a trunk at the same instant. Sometimes it is advisable, however, to provide that the trunks in a group will be selected successively: for example, if there are 10 trunks in a group, the trunk-selecting mechanism will test the trunks in order, starting at No.1 for each call, and seize the first trunk that is disengaged.

In Fig. 6A are given some curves showing results of observations made with the traffic-recording machine on groups of

trunks successively selected. The shape of these curves gave rise to the suggestion that two groups of 10 trunks each, for example, might be reduced without loss to two individual groups of 7 trunks each and a common group of 3 trunks, which would be a total of 17 trunks instead of 20, by connecting in multiple the 8th, 9th, and 10th trunks of each group after the manner

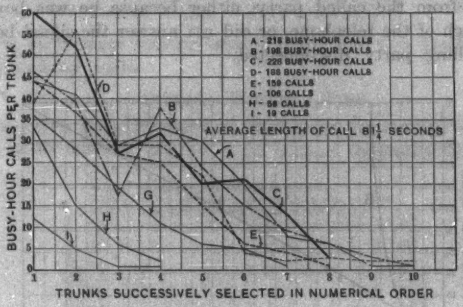

FIG. 6A

shown in Fig. 7. The effect of this method of connecting the groups together is illustrated in Fig. 8, which shows the load curves of the two groups of trunks overlapped in such a way that the one busy-hour call of the 10th trunk in each group is superimposed on the 9 busy-hour calls of the 7th trunk in the other group, while the 3 busy-hour calls of the 9th trunk in one group are combined with those of the same trunk in the other group.

It is argued by those who suggest this scheme that since, as shown in Fig. 6, a group of subscribers *A* making 175 busy-hour calls would require but 10 trunks and a similar group *B* would require but 10 trunks, while a group of subscribers making 350 busy-hour calls would require but 16 trunks, the arrangement in Fig. 8 satisfies all requirements; because it must be true that the peak loads in the two sets of 10 trunks each would practically never overlap, so that both groups of subscribers would never want the 3 common trunks at the same time, or else the curve in Fig. 6 and the law governing it are fallacious.

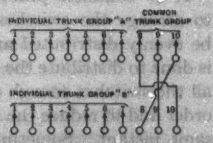

FIG. 7

There is one other factor to be considered, however, and that is the possibility of calls overhanging on the 3 common trunks, while some of the subscribers of the group *A*, for example, are not calling, and group *B* parties are endeavoring to secure access to the common trunks. The arrangement in Fig. 7 and Fig. 8 allows an extra trunk to overcome this objection, *i. e.*, allows

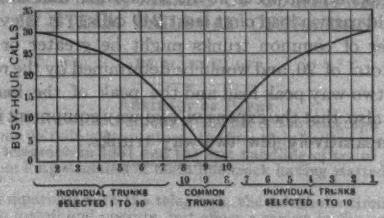

FIG. 8

17 trunks for 350 busy-hour calls, while but 16 would be required if all subscribers had access to every trunk.

Whether this arrangement will be justified by experience and become of practical value, the writer would not venture to say at this time. It seems probable that it could be practised to advantage where two-way trunk service is to be given. As the writer mentioned in a previous paper, there is generally a dif-

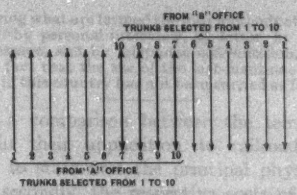

FIG. 9

ference in the times at which the peak loads occur on trunk groups carrying traffic in opposite directions between two offices, consequently the use of two-way trunks would reduce the number of trunks required. While such trunks have not been found feasible between large manual offices, they are nevertheless practical, and some of them are in use in automatic systems.

The obstacle in the way of their more general installation

is the increased cost of trunking equipment. This obstacle can be largely eliminated by the scheme illustrated in Fig. 9, which shows 16 trunks interconnecting two offices A and B, in such a way that each office has access to six individual one-way trunks and four two-way or common trunks. This plan allows for a peak load in either direction of 175 busy-hour calls, provided the two peaks do not occur at the same time, and the combined group would carry a load of at least 240 calls. It is evident that the number of common trunks might be greater or less than four in a total of 20, and would be determined by the relation between the two-way peak load and the peak of the load in each direction; also that the expensive two-way equipment is confined to the comparatively few two-way trunks.

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A COMPARISON OF THE TELEGRAPH WITH THE TELEPHONE AS A MEANS OF COMMUNICATION IN STEAM RAILROAD OPERATION

BY M. H. CLAPP

ABSTRACT OF PAPER

Brief historical descriptions of the use of the telegraph and the telephone on railroads are given, the first train having been handled by telegraph in 1851 and the first handling of trains by telephone on long stretches of main line track having started as late as 1907.

In comparison with the telegraph, the telephone circuits cost more to install and operate, but effect a saving in the operation of the railroad, both directly and indirectly, as it is possible to move trains over the road more rapidly.

The advantages and disadvantages in comparing the telegraph with the telephone are summarized as follows:

In Favor of the Telephone. Universality, saving of time, rapidity of transmission, psychological effects, promptness in raising offices, no necessity of specially trained operators, saving in expense of railroad operation, and best operation of circuit in heavy weather.

In Favor of the Telegraph. Flexibility in handling circuits, simplicity in installing, maintaining and operating, circuit best adapted for long distances, effects of distance in transmission, saving in cost of installation and maintenance, and the standard of maintenance.

In considering what are termed the four methods of communication, namely: by personal interview, by letter, by telephone or telegraph message, and by telephone conversation, attention is called to the fact that the use of the last-mentioned method by the railroads in this country has not been carried as far as it should.

IN MAKING a comparison between the telegraph and the telephone in their application to railroad operation, it is the purpose to state first the principal physical characteristics of each; secondly, the respective costs of providing and maintaining them, and, finally, the relative advantages and disadvantages of these two means of communication. A brief résumé of the early development will possibly serve to make clearer the situation which so long delayed the advent of the telephone for handling trains.

EARLY DEVELOPMENT

From the beginning of the operation of railroads in the United States in the early 30's, until the early 50's, a period

of twenty years, there was no system provided for rapid communication from one station to another. Trains were run on what was called the "time-interval system;" briefly, a ruling train had the right of one hour against all opposing trains of the same class. This practise continued for nearly ten years after Prof. Morse had sent his historical message from Washington to Baltimore. At about that time the Erie Railroad Co. constructed a telegraph line, which was first used, apparently, for handling local messages along the road. Finally, in 1851, a train was successfully handled by a telegraph order for a distance of 14 miles (22.5 km.) From this small beginning the handling of trains and messages by telegraph increased very rapidly, until, about ten years later, the telegraph was quite common on the railroads of the country. Contracts were early made between the railroads and the commercial telegraph companies whereby the same pole lines were used by both parties to support their wires along railroad rights-of-way. In the end, the telegraph became an established and invaluable adjunct in railroad operation, as will be described in more detail.

Although the Morse register was early done away with, and messages received entirely by sound, there was some opposition to this on account of the loss of the permanent record, especially when dispatching trains. This matter of not having a record was one of the principal reasons that the telephone was not sooner used for the dispatching of trains; but when this objection to the telephone is analyzed, we find that there is really no difference between the receiving of a message by sound on the telegraph as compared with receiving a message on the telephone, as no record is made in either case by the electrical or mechanical equipment proper. Apparently some of the persons who objected to the use of the telephone on account of its alleged lack of record, had in mind, when they considered the telegraph, the old Morse registers that were first used on the early telegraph circuits.

The railroads early began to use the telephone on different parts of their systems. As the commercial development of the telephone was very slow in this country up to 1890, it would apparently follow that there was not very much use of the telephone on the railroads during the same period. However, the records show that different railroads in the early eighties began to put in telephones for various purposes; not

so much, however, to replace the telegraph, as to replace messenger service and to serve as an auxiliary to the telegraph. The replacement of the telegraph by the telephone, to any extent, really began only six or seven years ago. It is only during this short period of time that extensive installations of telephone dispatching and message circuits have taken place, although beginning about fifteen years ago there were numerous telephone circuits erected between terminals and principal offices on some of the railroads. These long-haul talking circuits did not primarily replace the telegraph, but in most cases merely provided additional means for communication.

While trains were handled for short distances, principally in and about terminals, beginning back in the early nineties, it was not until the latter part of 1907 that any real attempt was made to handle trains on long stretches of main-line track by telephone. The Chicago, Burlington and Quincy road was one of the first to use telephone train-dispatching circuits on its main lines, and by the latter part of 1908 this company had a considerable mileage of its lines dispatched by telephone. The principal railroads in the East and the middle West at once began to install telephone circuits, so that at present there are some 70,000 miles (112,654 km.) of railroad in the United States dispatched by telephone. The use of the selective-ringing telephone circuit for the dispatching of trains was soon followed by the use of the same kind of circuit for the handling of messages. The growth of the telephone message circuit has, however, been very much slower than that of the dispatching circuit. The primary reason for this is the fact that the telephone message circuit does not meet the conditions on the average railroad to the same advantage as the dispatching circuit, there being more complications to meet than in the case of the dispatching circuit. In general, the message circuit requires a considerable amount of traffic to justify its use. However, it will only be a question of time when all telephone dispatching circuits are paralleled by telephone message circuits.

A Typical Railroad Telegraph System

The outside and inside plants used by different railroads necessarily vary to a large degree on account of the different sizes, resources, locations and conditions of the railroads served. A description will be given, therefore, of the system on one of the large transcontinental railroads with which the writer is

most familiar, with particular reference to the conditions about seven years ago, when the present extended use of the telephone for dispatching trains and handling messages had its beginning. It will not be necessary to describe in detail the pole lines used to carry the wires, either telegraph or telephone. It will be sufficient to say that these lines in the United States are in a great majority of cases constructed in accordance with the specifications of the Western Union Telegraph Co., which is substantial construction. These pole lines have at least thirty-five poles to the mile, where the number of wires to provide for is considerable, and in some cases 40, 50, 60 and even 70 and 80 poles per mile are used.

At first iron was universally used for telegraph wires, the size most used being No. 8 B.W.G., thoroughly galvanized. This practise, in general, was not changed as far as the railroads were concerned, except that a considerable amount of copper was put up for long-haul circuits. Of course, copper wire is used quite extensively near large centers or along the seacoast, or wherever corrosion would be troublesome. When copper wire is provided, No. 9 A.W.G. is generally used.

The average cost per mile (1.6 km.) for furnishing and erecting a No. 8 B.W.G. iron wire, including insulators, tie wires and pins, is about $25.00. This wire makes a very good telegraph circuit up to 400 miles without any intermediate offices. At this distance the wire can be worked either single, duplex or quadruplex. With intermediate (way) offices on the line the above-mentioned distance would be cut down to about 200 miles (321.8 km.). The matter of line insulation has a very important bearing on the distance that an iron wire or, in fact, any telegraph wire can be successfully operated. The distances given above assume a high grade of insulation. This mileage for the operation of iron wires, however, is ample for almost any division of a railroad, so that iron wire is very generally used in railroad local (way) circuits, copper wire being used between terminals and the principal points along the line. On the Northern Pacific system, when telephone circuits began to be extensively installed, about seven or eight years ago, there were the following mileages of copper and iron wires in use:

Copper,	4,000 miles (6437 km.)
Iron,	11,500 miles (18,507 km.)

There were practically two through copper wires from St. Paul to Tacoma, a distance of a little less than 2000 miles (3281 km.);

all the rest of the circuits on and between the different divisions were iron. At that time this wire plant was considered a very good one for the purpose for which it was intended.

The cost per mile for providing and erecting No. 9 B. & S. gage copper wire, including insulators, pins and tie wires, varies greatly with the price of copper, but assuming fifteen-cent copper, it would be, on the average, about $38.00.

The equipment of a telegraph office is comparatively simple and needs no description. The following costs will be of interest in comparison with the cost of telephone equipment.

A way station can be cut-in on a telegraph wire, including the battery (gravity) in the office, at a total average cost of $12.00

A switchboard (peg type) large enough to take care of ten wires, in and out, can be provided and installed at a cost of..... $42.00

The cost of providing and installing a twenty-five-line Western Union switchboard, with twenty wires cut in and out, and eight sets of telegraph instruments with necessary tables and battery, is about.... $140.00

Nineteen-conductor cable (No. 14 A.W.G.) suitable for connecting the wires from the line into the offices, can be provided and installed at an average cost of 30 cents per foot.

The average cost of providing and installing a quadruplex set would be about..... $200.00

The average cost of providing and installing a single-line repeater set would be about..... $50.00

At terminals, of course, more apparatus is necessary than at the way-stations along the line. However, a cost of $400.00 would provide and install the equipment in almost any terminal or relay office along the line, except the very largest. While the above-mentioned figures are approximate, and are averages for conditions on the transcontinental line with which the writer is most familiar, they are believed to be reasonable and to give some idea of the cost of providing telegraph circuits along a railroad.

Railroad Telegraph Traffic

On a railroad on which the telegraph is the only means for transmitting intelligence quickly from point to point on the system, except for short distances in and around terminals where the telephone is used extensively, telegraph communication is used by all departments and by a large percentage of the employes on all occasions and on all subjects. In fact, it is no exaggeration to say in general, that the sending of telegraph messages is made so easy that a great many more messages and words are sent than necessary. The telegraph office is usually located close to the Superintendent's office at division points, and at General

Headquarters is made as accessible to all departments as possible. In headquarters buildings, where a considerable amount of space and a number of floors are used, pneumatic tube systems are provided in order to carry the messages back and forth between the different offices and the telegraph office.

A considerable amount of railroad business is from its very nature urgent and requires as quick action as possible; for example, reports on the progress of trains over the division, the meeting of the various emergencies that arise, messages about shipments of different kinds, reports of the location of equipment along the road, and similar business.

Each section of railroad has, between terminals, at least one message wire and one dispatcher's wire, unless it is a very unimportant section such as a branch line, where one wire, in a great many cases, serves the purpose for handling both the messages and the dispatching. The length of railroad that can be handled by one telegraph message or dispatching wire depends upon the amount of traffic handled, the size of the towns along the line, kind of country through which the railroad is built, etc. On a busy single-track railroad, 100 miles (160.9 km.) would be a fair limit for telegraph dispatching of trains by the use of one circuit. The facilities necessary for handling the messages would, in a great many cases, be the same as those required for the dispatching, although there would be a great deal more variation in handling the messages than the dispatching. On an important section of railroad there is usually one message circuit that cuts into all offices along the line (way or local circuit) between the two terminals, with other circuits cutting into the more important points.

In order to handle the message service to and from the general headquarters a system of through circuits is provided between the different division points and the general offices. If the length of the railroad system requires it, relay and repeater stations are established. For example, on the Northern Pacific system there are four relay offices between St. Paul, Minn., and Tacoma, Wash. In these offices are located, with a few exceptions, the multiplex telegraph equipments (duplex and quadruplex); there the business is relayed to different offices and terminals to which direct wires are not provided. The wire testing is also handled at these points. On most railroads in the West the operators in the relay offices are on the pay-roll of the Superintendent of Telegraph and are handled directly by him. This

arrangement tends to give uniformity to the telegraph service on the system.

In order to give an idea of the extent of the telegraph system on the Northern Pacific, the following list is submitted, giving the assignment, the character of circuit and the mileage to the destination, of the principal telegraph wires working at the present time out of the St. Paul general office:

Circuit Assignment	Character of Circuit	Distance in Miles
St. Paul-Tacoma, Wash.	Quadruplex	1900
St. Paul-Missoula, Mont.	"	1250
St. Paul-Spokane and Pasco, Wash.	"	1650
St. Paul-Helena, Mont.	"	1130
St. Paul-Billings and Livingston, Mont.	"	1008
St. Paul-Dickinson, N.D., and Glendive, Mont.	"	667
St. Paul-Fargo and Mandan, N. D., local, 35 offices	Quadruplex to Fargo Single to Mandan	450
St. Paul-Fargo, N. D., and Dilworth, Minn.	Quadruplex	252
St. Paul-Duluth, Minn.	Duplex	152
St. Paul-Winnipeg, Man., Local, 32 offices	Single	483
St. Paul-Fargo, N. D., Local, 41 offices	Single	252
St. Paul Division, Local, 30 offices	Single	170
St. Paul-Duluth, Minn., Local, 40 offices	Single	152

This list includes only the principal circuits and does not include certain locals operating out of St. Paul to points in the immediate vicinity of the Twin Cities.

While there is no very accurate record of all the messages handled between all points on the system, the total is estimated at about 5,000,000 per year, not including any messages at present handled by telephone. This would appear to be a large number, even when it is considered that the Northern Pacific is operating over 6000 miles (9656 km.) of mainline track, and it shows, apparently, the free use that is made by this railroad of the telegraph message facilities. According to the writer's observations, the conditions in this respect on other railroads are not materially different.

The cost per message for handling communication by telegraph will probably average more on a railroad than the message cost of the commercial companies, because the messages are handled on the railroad in smaller offices, and on circuits on which the number of offices is larger. The labor cost per message in Northern Pacific relay offices is a trifle over two cents; in offices along the line it would be hard to say what is the actual cost per message, on account of the multifarious duties of the operators at most of these points.

Principal Advantages of the Telegraph

The principal advantages of the telegraph are its simplicity and its small cost, both as regards installation and in maintenance; this statement being made, of course, in comparison with the telephone. There are no very complicated circuits in connection with the telegraph, especially at the great majority of the offices along the line. The ordinary lineman has no difficulty in learning how to install and maintain sets of telegraph instruments, and with a little experience, he is able to install duplex and quadruplex apparatus, and Western Union peg switchboards. In general, no particular care is necessary in running telegraph circuits, with respect to one another, in order to avoid induction either in the offices or on the line. In making the last statement, however, the author fully appreciates that telegraph circuits have been seriously interfered with by induction in certain cases; the conditions in mind are those which exist, as a rule, on the great majority of railroads where the telegraph is used. Also, a telegraph circuit will operate under defective maintenance conditions, such as loose connections, unsoldered joints, defective office and cable-box wiring, high resistances in series with circuit, etc., where a telephone circuit would absolutely fail. In other words, the telegraph circuit usually has a considerable amount of margin in operation and will stand a large amount of neglect and abuse. The cost, as already indicated, is small for both line wires and office equipment, and while copper wire is used to some extent, iron wire serves the purpose in a great many cases where it would not be possible to use it in connection with the telephone. The telegraph, also, has the advantage of being a very accurate means of communication. A telegraph sounder makes very clear and distinct signals, and to an expert operator, there is no question as to what has been transmitted; and, if the wire is working at all, the distance is not much of a factor, because the sounder is in a local circuit.

Disadvantages of the Telegraph

The great disadvantage of the telegraph is its lack of universality. It requires a specialist in order to operate it; that is, an operator who has spent a considerable amount of time, years in some cases, in order to qualify for the work. When carrying on a telegraphic correspondence, one is always working through some one else, never directly. This condition is satisfactory

in handling some kinds of business, but not for all kinds. The train conductor out on the line can, in the case of an accident, send messages by telegraph to his superior if there is a telegraph office near at hand in which operators are on duty, and accomplish certain results; however, if he can talk directly with his superintendent, a great deal more can be accomplished. The same is true of the section foreman out on the line, the superintendent in his office, and other employes on the division.

There is a decided lack of ability to secure information of the thousand and one emergencies that arise on a railroad, by telegraph, as quickly as desirable. This is due, first, to the fact that comparatively few employes on the system can use the telegraph directly, and second, to the fact that the telegraph is slower as a means of transmitting intelligence than its great competitor, the telephone. It takes longer to transmit a train order by telegraph than by telephone. This disadvantage of the telegraph is especially noticeable when one attempts to discuss any subject over the wire by telegraph, even between expert operators; and where it is obligatory to write out the necessary questions and answers in the form of messages to be sent and received by operators, the superiority of the telephone is even more evident.

The telegraph is at its best in handling messages that are comparatively brief, making definite statements or reports or answering definite questions. As soon as one attempts to ask several questions on different phases or points of a subject, in other words, attempts to discuss it, the telegraph becomes a comparatively slow means of communication.

Trouble is also experienced from delay in getting the offices along the line to answer their calls. In case several wires are looped into an office, and the operator is busy, he may not hear the call when made, or perhaps will pretend that he does not, and it is impossible to prove definitely whether or not the call came in properly. Some attempts have been made to meet this difficulty by providing a telegraph selector at each station that would respond to a certain combination of signals and ring a bell for the particular station desired. However, this device has not been used to any extent by the railroads.

There is, also, the trouble experienced in obtaining operators, which in recent years has become a serious problem, especially when times are prosperous. A railroad which depends at present entirely upon the telegraph has considerable difficulty in se-

curing operators of any kind, without much regard for their ability. There has been a great falling off not only in the supply, but in the grade of men who enter this field. Twenty or thirty years ago, the conditions were strikingly different, for the reason, perhaps, that there were not then the many opportunities for men to enter electrical pursuits that there are today. Then there is the influence of the labor organization. Practically all railroads have a strong labor organization of telegraphers with which to contend. In making promotions, the labor union appears always to desire to have seniority in the service made the primary consideration, and ability or fitness for a position the secondary consideration. In general, this seniority idea tends to drive the best men out of the service and prevents the ablest men from learning to telegraph.

The Railroad Telephone Plant

The outside plant necessary in connection with the telephone is substantially the same as that required for the telegraph, except that in practically all cases copper wires are used. Two wires, however, are necessary in order to provide a metallic circuit, and they must be arranged side-by-side on the crossarm and transposed at frequent intervals in order to avoid induction and cross-talk from other circuits. All cables used in looping telephone circuits into offices must have their conductors arranged in twisted pairs, in order to avoid cross-talk.

The great difference between the telegraph and the telephone plants is in connection with the inside plant. Instead of the comparatively simple apparatus already described, the telephone equipment is more or less complicated. There is first the private branch exchange, which has become so important a part of railroad operation in so many places. These exchanges are, in a great many cases, rented from the telephone companies at the usual rates. However, there are numerous exchanges privately owned and operated, the latest type to be used being the automatic switchboard. Arrangements are made to bring into these branch exchanges the telephone lines of the railroad between the different division points and terminals, to facilitate ready intercommunication. Also, in some cases, arrangements are made so that a railroad official can talk from his office over the lines of the railroad company to any subscriber's station in the public exchange system in a distant city or town.

The cost of telephone circuits for use between the exchanges along the line depends, of course, on the kind and the size of

line-wire used. The cost per mile of a No. 9 A. W. G. copper circuit in place, on the basis of fifteen-cent copper, is about $75.00. The cost per mile of a No. 6 A. W. G. copper circuit on the same basis, would be about $150. The latter circuit would give, under ordinary conditions, satisfactory telephone transmission up to 1000 miles, while the former would be satisfactory up to about 500 miles (804.6 km.).

The telephone dispatching and message circuits are the most interesting and peculiar to the railroad service. The provision of a means of selectively signaling the different stations along the line was a problem that took some time to solve satisfactorily. These selectors have different designs and principles of operation. In general, the selection is made by a step-by-step mechanism which responds to a certain number of pulsations or combinations of pulsations sent over the line, making it possible to arrange a large number of selective combinations, and thus signal any given station at will, without disturbing the others. Selectors are now made that are very efficient in operation, and will call selectively as many as 125 stations on the same line. At the stations along the line a special form of telephone set is installed for the use of the operators. These sets have a certain combination of apparatus and wiring that provides a so-called "booster" effect in transmission. This is secured by a switch which is so connected in the circuit that when the operator is talking, the receiver is short-circuited, and when the operator is listening, the receiver is connected directly to the line and the transmitter disconnected. Head telephones are provided so that the operator may have free use of his hands. In the dispatcher's office, special telephone sets are used which are wired like the sets at the way stations, except that breast-plate transmitters are usually provided so that the dispatchers can move about sufficiently in making entries on the train sheets, which are usually of considerable length and width. Some of the railroads have experimented with, and are using with some success, loud-speaking transmitters and receivers for the dispatchers. This apparatus, however, has not been developed to the point where it can be used successfully in all cases. Loud-speaking apparatus is greatly to be desired, as the dispatchers complain quite generally of the hardship of wearing continuously the head telephone and the breast-plate transmitter.

The batteries used at the way stations are in most cases com-

posed of dry cells; they are also used in the majority of cases for the line-battery in the dispatcher's office. These cells are, on the whole, the most economical, as the line current necessary to operate a selector is rarely over 10 milliamperes and in some cases is as low as 1.5 milliamperes. However, small generators are used in some cases to furnish the necessary ringing current; storage cells, also, are used, and both are economical where the circuits are long and there are numerous busy stations on them. In a few cases secondary battery is used at the way stations, but it is not general practise, primary cells being in the great majority of cases the most economical. Wet primary cells are often used for providing the current for the dispatcher's transmitter.

The cost of providing a selector circuit ready for operation under average conditions is as follows:

Cost per station of providing and installing the selector and telephone equipment, protectors and wiring, both outside and inside of the offices, $80.00.

Cost of providing and installing the necessary telephone and selective apparatus, including the battery, in the office of the dispatcher, $250.00. Assuming that a telegraph pole line is already available, the cost of a suitable telephone circuit has already been placed at $75.00 per mile, so that the cost of providing and installing a selective telephone circuit along 100 miles (160.9 km.) of railroad, where there are thirty offices to serve, would be a little over $10,000.

A telephone circuit as described above can be used either as a dispatching circuit or as a message circuit. In arranging for the handling of messages by the telephone, the operator at the terminal office usually remains on the line continuously, thus requiring signaling in one direction only. Often separate rooms are provided for the telephone operators; but in some cases they are placed on opposite sides of the same tables which the telegraph operators use, with good results. The number of messages that can be handled on a telephone message circuit will average twice the number that can be handled by telegraph between the same offices, especially if a typewriter is used in receiving.

Two very useful and time-saving auxilaries which are available with a telephone system are installations of telephones in booths or boxes along the railroad right-of-way at so-called "blind sidings" (where no regular operators are employed, and where there may be not even a station building) and portable telephones for the use of the train crews. Telephones of these

types can be used to great advantage by the trainmen in handling the many emergencies that arise, and are also of material assistance to the dispatcher, in reducing train delays. Order-forms for use of the trainmen are usually provided along with the telephones installed in booths or boxes and, in some cases, special forms of registers are provided in which the order forms are placed so that three copies can be made of all orders transmitted to the trainmen, one copy in each case being given to the engineman, the second copy to the conductor, and the third copy remaining in the machine as a record.

The portable telephone has obvious advantages in the respect that it can be used at any point along the road, by making temporary attachment to the telephone line-wires. Some of the railroads, however, have installed telephones in boxes or booths along the right-of-way every half mile; in such cases portable telephones could hardly be used to advantage. The telephones along the right-of-way are usually connected to the dispatching circuit so that the trainmen can talk directly to the dispatcher. Where telephones are provided every half mile, they are usually connected to a separate line-circuit, and provisions are made at way stations for switching it to the dispatching circuit.

The cost of a booth installed along the right-of-way, with the necessary telephone apparatus, depends on how elaborate an installation is desired; a very substantial and satisfactory installation can be provided for $90.00, but this can be reduced to possibly $30.00. A good portable telephone can be purchased for $12.00.

In addition to the uses already described, there are various miscellaneous ways in which the telephone can be used on a modern railroad. Telephone sets are placed in the observation cars of limited trains and connected to the railroad company's branch exchange, so that passengers can talk to parties in the city from which the train is leaving, up to the time of departure. The telephone is often installed in freight sheds and in freight yards so as to provide a means of ready communication from one point to another. Special types of telephone sets are installed on the desks of officials and so wired that conversations can be carried on with other officials in the same building by ringing a bell as a signal and then simply talking in an ordinary tone of voice into the telephone set, without the use of the ordinary receiver or transmitter. Local telephones are installed in the homes of trainmen for use in calling them for duty, thus saving time and avoiding the expense of employing messengers.

The method employed in handling train orders by telephone contains some points of interest. All figures or names of stations occurring in the order are spelled out letter by letter, both in the giving of the order and in all repetitions; also, in handling a "31" order,[1] the name of the conductor is spelled out. The dispatcher writes the order in his train-order book at the same time that he telephones it to the operator or operators on the line. Each operator who receives the order repeats it back to the dispatcher, the dispatcher underlining each word or number as repeated. In operating a message circuit, the same general practise of spelling out words and figures is followed as in the case of the dispatching circuit. The cost of maintenance of the telephone is always more than the telegraph, for the reasons that the telephone is more complicated and has more equipment. In the author's opinion, specially trained men should always be employed to maintain the telephone station equipment, although on some railroads the section linemen are required to maintain the telephone equipment; the last plan, however, produces in most cases indifferent results, in the author's opinion. In order to maintain properly four selective telephone circuits, having an average length of 100 miles each, at least one telephone inspector should be provided at a monthly rate of $85.00 with expenses, and there should be additional force if there are many telephones maintained at different "blind sidings" along the line, or special apparatus installed at various terminals, private-branch exchanges, etc. All of this expense is practically in excess of what is necessary to maintain the telegraph to handle the same work, although, as already indicated, the telephone handles a great many transactions that were never attempted by telegraph.

Comparative Advantages of the Telephone

The advantages of the telephone are many; some direct, some indirect and some psychological. The first and most important, in the author's opinion, is that it permits direct dealing between the parties desiring to transact business. The superintendent can talk directly with his subordinate; the chief dispatcher can talk directly with the trainmen out on the line, and any two employes can deal directly with one another, if the proper telephone facilities have been provided. This is what might be termed

1. A form "31" order requires the signature of engineman and conductor, whereas a form "19" order does not: see "Standard Code" of the American Railway Association.

the universality of the telephone as compared with the telegraph; every one from the president to the section foremen can use the telephone directly. The telephone, compared with the telegraph, is a great time saver on account of its speed of transmission. Train orders can be handled more rapidly by telephone than by telegraph. This is due to the fact that the orders can actually be transmitted faster over the telephone; also, to the fact that the operators along the line can be made to answer the calls on the telephone bells quicker than their calls on the telegraph. The primary reason for this last condition is the use of four-inch vibrating bells for way-station calling signals, which can be heard from some distance. Again, an operator does not know what is taking place on a telephone line until he comes in on the circuit, while, with the telegraph, the operator by listening can read all that is being sent and, in some cases, can judge as to the relative importance of the calls for his office. A call on the telephone always involves an uncertainty as to what is wanted or who is calling; therefore, in order to be on the safe side, the operator will unconsciously drop any work in which he is engaged and answer the telephone bell when it rings. This peculiarity of the telephone constitutes one of its psychological advantages referred to above. Furthermore, the calling bell is so wired in the circuit that the dispatcher hears it ring, thus removing any doubt as to whether the bell actually rang or not. This is a very important point in favor of the telephone, as it removes any chance for an argument between the dispatcher and the operator as to whether the latter was called.

Since the dispatcher remains on the circuit continuously, the operators along the line can communicate with him without calling, by simply coming in on the circuit and stating whatever information they may have to communicate. On this account it naturally follows that more detailed information is obtained as to train movement, and that the dispatchers can keep in closer touch with their work. In using the telegraph a train dispatcher is not able to transmit his thoughts by one-tenth the speed he could express himself by word of mouth. While a dispatcher cannot send a train order ten times as fast by telephone as by telegraph, he can carry on conversations with operators and trainmen along the line at this rate, which is a great advantage to all concerned. Also, with the telephone, the necessity is removed of operating trains through the medium of a large number of men of varying ability. Then there is

the human side of the telephone system; the men along the line get very much better acquainted over the telephone than over the telegraph, and coöperate to greater advantage. This condition was largely unknown when using the telegraph, and is not the least of the advantages in the use of the telephone.

By the use of the telephone, the field from which dispatchers and operators can be recruited is naturally broadened. It is no longer necessary on a railroad where the telephone has been installed with a sufficient number of circuits to keep the service intact, to depend on telegraph operators, in other words, specialists. There is, for example, one division on the Pennsylvania Railroad where out of about 400 operators' positions along the line, it is necessary to fill only eight of them with telegraph operators. This is a very important point for consideration in these days when, as already stated, the supply of telegraph operators is not equal to the demand. Also, it is possible to use as a dispatcher an employe other than one who has obtained his experience in the telegraph or telephone service, as, for example, a freight or passenger conductor.

While a telephone circuit is, in most cases, more susceptible to outside influences than the telegraph, experience shows that in heavy weather, heavy fog, mist, rain or snow, less trouble is experienced with the telephone than with the telegraph; and the telephone is affected only to a small degree by earth currents or by the aurora borealis.

Finally, we have for consideration the saving in the operation of the railroad by the use of the telephone. Unfortunately, it is hard to show in all cases a saving, because many of the best-known economies are more or less intangible. One is generally sure that he is saving time by using the telephone, and it seems at least a fair assumption that there is a corresponding money saving. The psychological effects can be capitalized to some extent, but it is generally difficult to do it. In the way of direct saving, the ability of the dispatcher to get his trains over the division quickly, thereby economizing in operating expenses, is the most evident, and easiest to understand. This is especially noticeable in the amount of overtime that can be saved in the pay-rolls of the trainmen and the enginemen. As it is conservatively estimated that the trains can be handled over a division from 10 per cent to 20 per cent more rapidly by telephone than by telegraph, an approximate estimate of the overtime saved can be prepared by considering

a certain operating division before and after the telegraph is replaced by the telephone. For example, on a certain division where the Northern Pacific is now installing the telephone, both for handling trains and for handling the messages along the line, it has been estimated that a saving of about $200 per month will be made in overtime paid to trainmen and enginemen, to say nothing of the other indirect savings of which mention has already been made. In some cases, a direct saving can be made by using a smaller number of dispatchers when handling a given section of railroad by telephone, as compared with the telegraph. For example, there is a division on the Northern Pacific which is made up of four consecutive districts, having an average length of a little over 100 miles each. Part of the year, the four districts can be handled by using two telephone dispatching circuits; but when there is considerable business on the railroad, four dispatching circuits are used. It would be necessary with the telegraph, to handle the four districts by using four circuits at all seasons of the year. As it requires three dispatchers to handle one dispatcher's circuit during the entire twenty-four hours, and as the salary of a trick dispatcher is $155 per month, the abandonment of any of these positions even for a part of the year is a very desirable thing from the standpoint of saving in expenses.

Savings are also made possible by the installation of telephones in booths or boxes at or near small and unimportant stations along the line where operators have been employed, thus resulting in the closing of these stations for a portion of the day, at least, and reducing the number of operators. In some cases, less expensive operators are employed when the telephone is installed; this practise is quite common on some of the railroads, and is done both at the stations along the line and in the offices at terminals and headquarters. In the latter case female employes are often used to advantage, as all that is necessary is a reasonable familiarity with the business to be handled and the ability to operate a typewriter.

Disadvantages of the Telephone

The principal disadvantage of the telephone as compared with the telegraph is its cost of installation and maintenance. However, these increased costs are overcome by the savings that are made possible. Another disadvantage is that the telephone, in the present state of the art, is not adapted, on account of excessive cost, for use on the railroad for any considerable

distance. While there is a circuit about 1000 miles in length in operation on one railroad in this country, at least, this circuit is used entirely as a talking-circuit and is not used for message work. It requires a good margin of transmission to handle messages over a telephone circuit and, according to the author's experience, a circuit equating to more than 26 miles of standard[2] cable should not be used in railroad service; at least, not in connection with handling trains or messages.

While it is possible to construct a telephone circuit 2000 miles (3218 km.) long, or even longer, that would have the proper transmission efficiency, it will apparently be some time before a railroad can justify such a circuit, from the standpoint of first cost and maintenance expense, and benefits derived. The telegraph will probably continue to handle the messages for the long distances, such as 500, 1000, or 1500 miles (804, 1609, or 2414 km.), for a considerable time to come.

The telephone is not as flexible as the telegraph when making patches in cases of trouble on the regular wires. For example, suppose that the entire pole-line is down at some point between two terminals, it is very easy to re-establish a telegraph circuit over some second route, even though it be very circuitous. If the circuit is too long for direct working, repeaters can be cut into the circuit at intermediate points. For example, it is entirely possible for the Northern Pacific to obtain a circuit from the Western Union Telegraph Co. via Omaha, Denver, Cheyenne, Ogden and Portland, and work directly between its St. Paul and Tacoma offices. But it is impossible to establish an emergency telephone circuit for the distance involved in the above example, or for considerably shorter distances.

The telephone requires a much higher efficiency of maintenance than the telegraph. This is not, strictly speaking, a disadvantage. In fact, the telegraph wires and apparatus should be maintained as well as the telephone system, but in practise this is not done except in very few cases. Also, there are more delicate parts in the telephone apparatus, to get out of order, than in the telegraph. The required efficiency of maintenance is not as easy to establish, on a railroad, as might be thought. The telegraph and telephone plant is necessarily spread out over the entire system, without very much of it in any one place; this makes it difficult to secure adequate super-

2. Standard cable has a resistance of 88 ohms per unit (No. 19 A. W. G. metallic) and a mutual capacity of 0.054 microfarad per mile.

vision, and it is not easy to impress upon the different employes who have to do with the maintenance of the plant, the importance of keeping the lines and apparatus in proper condition.

Summary of Relative Advantages of the Telegraph and the Telephone

The following summary presents the respective advantages and disadvantages of the telegraph and the telephone.

The advantages of the telegraph are: (1) Flexibility in handling circuits; (2) simplicity of installation, operation and maintenance; (3) best adapted for long-distance service; (4) least affected by distance, in respect to transmission efficiency; (5) low cost of installation and maintenance; (6) the necessary standard of maintenance is not difficult to secure.

The advantages of the telephone are: (1) Universality; (2) saving of time; (3) rapidity of transmission or dispatch of business; (4) psychological effects; (5) minimum delay in getting offices to answer calls; (6) lack of necessity of trained specialists to operate the service; (7) saving in total expenses of railroad operation; (8) minimum impairment of transmission efficiency in heavy weather.

Applications of the Telephones

As yet very few railroads are using the telephone as much as they could or should. Because many of the economies with the telephone are more or less intangible, railroad managers are rather cautious in authorizing its wholesale installation. They are usually ready to authorize telephone dispatching circuits, as the savings from them are more easily understood than in other applications. In the author's opinion, the up-to-date railroad of the future will handle its operating divisions entirely by telephone, the telegraph being used only for message work for long distances between the terminals and the general headquarters. On the divisions, the typical way office will have no telegraph instruments, and will depend entirely upon the telephone for handling all messages. At all terminal points and important offices along the line, private-branch exchanges will be installed, which will be connected with each other by means of talking circuits, so that any two employes on the same division or adjacent divisions can communicate with one another easily and quickly. Telephones will be installed in booths or boxes along the right-of-way at frequent intervals, such as every half-mile, and the necessary lines and apparatus provided

so that trainmen, sectionmen or any one out on the line can obtain ready communication with persons with whom they may have business to transact. Where portable sets can be used to advantage, they will be furnished to such employes as trainmen, sectionmen, linemen, signal maintainers, etc., so that connections can be made directly to the telephone line-wires at any point along the line. Ample telephone service will be provided at all points, especially where private-branch exchanges are installed, so that all employes having any legitimate need to talk to one another can do so without delay, whether in the same city or town, or at points on the same division, or other divisions, within a possible limit of 1000 miles. Also, the railroads will not forget to provide ample service so that the public can reach certain authorized employes by telephone, promptly, when necessary.

The above outline of the applications of the telephone to the needs of a railroad is not entirely prophecy, since there are railroads in this country already using the telephone, on portions of their systems at least, almost as extensively as contemplated in the foregoing description.

There are four general methods of communication, namely: by personal interview, by letter, by telegraph or telephone message, and by telephone conversation. There are certain business transactions that can best be handled by only one of the above methods; there are others that can be handled by two or more of these methods; and in some cases, by any one of the four. Without doubt there is always one of these methods, as a rule, that is best adapted to any particular transaction. While a great deal of traveling is done by railroad men, there is still, in the author's judgment, a lack of personal contact in a great many of the departments between the man in charge and the men in the field; in other words, there is a lack of supervision. There is probably no lack in the number of letters written; and there is no doubt at all that too many telegraph messages are sent. The telephone as a means of communication is not, however, used as it should be on the railroads in this country. As already pointed out, the local use of the telephone has been well developed in a great many places, and the same is true of its use in dispatching trains; but its universal application as a means of communication, and its substitution for and its use as an auxiliary to the telegraph, have only in a very few instances been carried to a logical conclusion.

DISCUSSION ON "TRAFFIC STUDIES IN AUTOMATIC-SWITCHBOARD TELEPHONE SYSTEMS" (CAMPBELL) AND "A COMPARISON OF THE TELEGRAPH WITH THE TELEPHONE AS A MEANS OF COMMUNICATION IN STEAM RAILROAD OPERATION" (CLAPP), NEW YORK, MARCH 13, 1914.

William Maver, Jr.: I think it may be safely stated that if the telephone had been invented before the telegraph, and had been in use on railroads for train dispatching and the transmission of messages, up to the limit of distance of which it is capable, there would have been very little disposition on the part of railroad managers to displace the telephone by the telegraph, but when the telephone appeared the telegraph was well established on railroads, and its small cost and simplicity have served to give it the stability in railroad service that it has acquired.

The question of the more extended use of the telephone on railroads was under discussion before the Association of Railway Telegraph Superintendents at the Annual Convention in Wilmington, N.C., in 1899, and the chairman of the convention expressed the views of the Association when he said that the railroads as a general thing do not earn large dividends, and they do not care to spend much money on telephone lines. Although the subject of the use of the telephone for train dispatching was mooted in 1899, it was not until 1907 that its use for this purpose on a large scale began, and its employment in this service imperatively demanded the development of means for rendering it practically available, which demand was met by the introduction of selective ringing.

I think the idea prevails that iron has been quite largely displaced by copper wire for telegraph purposes, and that when iron is used in new work it is to give strength to the line. One important claim for the employment of copper wire in telegraphy, in addition to its superiority electrically, has been that when iron, by reason of corrosion, has become valueless, copper wire still has high intrinsic value as junk.

My experience on frequent occasions when I have had the option of using the telegraph or the telephone over distances ranging from 200 to 1000 miles has been quite favorable to the telegraph as a means of quick, reliable and intelligent communication between expert operators, chiefly due to an uncertainty as to certain words in telephone conversations, which frequently called for repetition. My observation of the operation of the telephone in some cases seems to indicate that when it is used regularly for questions and answers, the purport of which is generally understood by both speakers, conversation is easy. I have noticed this particularly in cases where the telephone is used as a means of communication between different sections of large manufacturing plants, where illiterate

workmen exchange information freely concerning the work in which they are engaged. When, however, subjects foreign to this work are broached to them by telephone, they are often at sea. While it is true that Mr. Clapp quite properly stipulates a high factor of transmission efficiency for the telephone circuits for this railroad service, I believe that some, at least, of the success of this service between dispatchers, station agents and conductors may be due to their familiarity with the nature of the subject discussed, although of course the precaution of spelling out the words of train orders, letter by letter, and repeating back the order to the dispatcher, is almost a sure preventive of error.

The fact that telegraph operators require months or years to become proficient is a great disadvantage of the telegraph as compared with the telephone, and the further fact that the labor element utilizes this condition to enforce its demands has, no doubt, been an important factor in forwarding the employment of the telephone for the movement of railroad trains.

Mr. Clapp makes the point that the telephone operator at a station cannot hear what is passing on the line until he cuts in, whereas the telegraph operator can hear everything. Seemingly, there is nothing to prevent the railroad telephone operator from cutting in at times from curiosity. Again, there have been cases in which it was important that the telegraph operator had heard the dispatcher's messages to other stations.

The point brought out relative to the time gained by using the telephone in the movement of trains and in other directions, and the consequent saving in the pay-rolls of train crews, as well as the savings due to the displacement of expensive telegraph operators by less expensive telephone operators in many places, is a strong one, although the aggregate saving thus far does not appear to be great in the specific cases discussed by Mr. Clapp.

The change from the telegraph to the telephone in railroad service is quite a radical one, and has to face the condition that the telephone, like the telegraph, is not directly a revenue producer for the railroad companies, and hence does not always receive the recognition that its importance in the actual operation of the railroad system warrants. Considering, however, the fact that it is only within the past two years that any railroad officials have had the temerity to authorize the substitution of the telephone for the telegraph as a means of communication in steam railroad operation, the progress thus far made in that direction is really noteworthy.

William E. Harkness: The use of the telephone in the transaction of railroad business will be greatly increased in the future, and in many cases it will supersede the telegraph. There are, however, certain classes of railway communications which can be handled more economically by telegraph, so that we need not anticipate the complete elimination of the telegraph

as a means of communication. Whether telegraph transmission in the future is to be performed manually or by machine remains to be determined, but this phase of the situation is at present receiving considerable attention.

Mr. Clapp has given figures covering the average costs of line construction and station equipment on single- or double-track railroads. The amount covering station equipment may be increased to as high as $200 per station on multi-track trunk lines under complete telephone operation where the number of lines entering a way station varies from five to ten. Roads of this class are, however, few.

It is interesting to note that the annual saving in overtime by the use of the telephone on the one division mentioned amounts to 24 per cent on the investment, also that the saving given does not include the saving in time of motive power nor the saving in coal consumption, which are two of many expenses which are indirectly affected. Unfortunately, these savings cannot be calculated in advance when presenting the advantages of the telephone to the railroad management.

It has been found that the train dispatcher operating by telephone is under less strain than one operating by telegraph, and can handle practically double the amount of work he has been handling by telegraph. This in some cases has resulted in the extending of his district, as mentioned by Mr. Clapp. The savings in salaries alone in such a case will approximate $5,000 annually, which is equivalent to 25 per cent on the first cost of the telephone circuit over the two districts covered.

While the cost of telephone line construction is nearly double that of the corresponding class of telegraph construction, it must be remembered that the facilities for communication have been more than doubled. In the first place, the speed of transmission has been increased. The average railroad Morse operator does not send over 25 to 30 words per minute, whereas by telephone the same man will transmit at the rate of 50 to 75 words per minute, the latter rate being in excess of the maximum manual Morse record. One factor having a bearing on this matter, which differs from that of a commercial basis, is the greater length of railway messages.

Secondly, in addition to the two wires being used for telephone conversation, they provide an additional telegraph circuit at an expense of not over $100 for auxiliary equipment for simplexing the circuit: or, if two parallel telephone circuits are available a third or phantom telephone circuit can be secured, capable of good commercial transmission for distances up to 500 miles, at an expense of approximately $500. In one case where this has been done, a saving of $100 per month has been made in long distance tolls at one terminal alone, and no value placed on the time saved or increased use of the service.

The telephone for some time to come cannot compete with the telegraph in handling messages over distances of 1000 miles

or more. It is believed that the relation between long and short haul traffic will be approximately the same on railroad and commercial circuits, so that it would seem advisable to study the traffic handled before proceeding with the construction of long telephone lines.

While at present on the average railroad the telegraph is more flexible from the standpoint of additional facilities and the ease with which circuits can be patched in case of emergency, this condition will gradually change as the number of telephone circuits is increased on each railroad. It is not anticipated, however, that the telephone will be able to compete with the telegraph when it comes to making up long roundabout circuits to reach distant points. For the average division, however, the same flexibility can be obtained by the use of adjacent circuits or an interchange of facilities by connecting railroads.

It may be well to state here that the success of the telephone for train dispatching depends not upon telephone equipment, but upon the means of selectively calling the individual stations.

It is of interest to note that the difference in time taken by operators to answer a telegraph sounder call and a selective telephone call has in some cases been so pronounced as to occasion the installation of telegraph selectors on some railroads to improve the telegraph service. In fact, there has been a marked revival of selective telegraph calling in both railroad and commercial service.

It has been stated that the use of the telephone for message service demands heavy traffic. This is true when a supervising operator is employed to do the calling of stations as described, but where the circuit is arranged so that any station can call any other station the telephone is particularly adapted for lines carrying light traffic, as for instance, the branch lines running from the main trunk line.

With regard to the labor situation, the fact that a man is an operator is secondary to the fact that he is a railroad man, and there have been very few cases where employees have lost their positions on railroads because they were telegraph operators, and replaced by telephone operators. The railroads, however, have a larger field from which to select their employees, and they are able, therefore, to select a better class of employees than they have had heretofore.

The telegraph departments of the railroads are not earning departments, and therefore have not been given the consideration that other departments are given when it comes to spending money. The railroad is practically inoperative without the telegraph or telephone departments, and sooner or later more consideration will be given to them.

R. N. Hill: The implied conclusion in Mr. Clapp's paper that the telephone has a sufficient margin of merit over the telegraph as a medium for the transmission of intelligence in railroad operation to warrant its somewhat greater cost, seems

to be borne out by practise. We note, however, that in the comparison of costs of inside and outside plant, the facilities provided by a single telephone circuit composed of two No. 8 gage copper wires, have been compared directly with the facilities provided by one iron telegraph wire working duplex or quadruplex, and it seems that it would only be fair to recognize the fact that one pair of telephone wires is capable of supplying a telegraph circuit in addition to the telephone circuit, and that this telegraph circuit may be duplexed or quadruplexed. Also, if there are two similar pairs of wires on a pole, properly transposed, we may obtain from them not only a train dispatching and message circuit, but we may in addition obtain a third telephone circuit and a telegraph circuit; in other words, four circuits from the four wires. The cost of obtaining the additional telephone and telegraph circuit is only nominal.

Therefore, it would be more nearly fair to compare, as far as outside plant is concerned, the cost of one No. 9 A. W. G. wire with the cost of one No. 8 B. W. G. iron wire. On this basis the telephone will appear much more favorably in regard to initial cost.

I have noticed further, that the telephone circuit which has been especially designed for use in the railroad field has been referred to as the so-called "booster," and so that there will be no misunderstanding it would be well to emphasize the fact that it is only so called. It might better be called a "conservation" circuit, for in fact the gain in transmission which is effected, which in amount is in the neighborhood of four miles of standard cable, is due solely to the fact that we eliminate the dead loss which occurs in the ordinary telephone circuit by, so to speak, "talking out" through the receiver at that station, and receiving through the secondary of the induction coil. In still other and more general terms, it delivers to the line, when transmitting, more nearly all of the energy which the transmitting element is capable of producing, and at the receiving station it uses a larger percentage of the energy available in producing the necessary effect in the receiving instrument.

I gather from the statement regarding the use of booths at frequent intervals along the right of way for use in case of emergencies, that it is the usual practise to run a separate pair of wires to which these stations are connected, and to rely on a switching arrangement at an adjacent station at which there is an operator to connect the party to the train line. I am wondering if the intent of this arrangement would be to free the train wires of the load of a multiplicity of stations which are not used except at rare intervals. If so, it would seem more economical and the same result could usually be accomplished by the use of a reliable automatic cut-out switch, either operated by the closure of the door of the booth, or from the hasp of the padlock, to insure that the sets were disconnected from the line when not in use. I understand this is quite common practise with a number of the railroads.

D. P. Grace: Mr. Campbell's paper describes the apparatus for recording the time on trunk lines, and that is particularly applicable in automatic exchanges, but I think it might be of considerable use in manual exchanges.

Regarding Mr. Clapp's paper on the advantages of the telephone and telegraph, the most interesting thing to consider, perhaps, is that, in a measure, the dispatching circuit is an automatic system, in that the supervising operator or dispatcher uses the automatic mechanism for calling the operators along the line. As time goes on, it will be interesting to know how much more use is made of automatic apparatus in the general extending of the telephone system that Mr. Clapp predicts. There is a possibility that the automatic apparatus may be used at the terminals as well as in the dispatching along the line.

Mr. Clapp speaks of the delicacy of telephone apparatus and the increased cost of maintenance over telegraph apparatus. Now, it is true that telephone apparatus as placed in the hands of the subscriber along the line is, as a rule, delicate. The telegraph apparatus, on the other hand, is much stronger. Apparatus to be supplied for a telegraph line, or a telephone line, especially on a railroad, should be very substantially built, and if care is given to designing, I think much of the present maintenance charge could be eliminated.

In many railroad systems where telephone circuits have been used for message purposes, there has been a great deal of trouble due to poor transmission. This has most generally been traced to the lack of knowledge on the part of railroad telegraph people in the operation of these circuits. They have assumed that they could be used much the same as telegraph lines, and have connected into the circuit many miles of rubber-covered wire and iron wire, and have even run these wires through many private branch exchange switchboards, the result being that the transmission was very poor. Wherever there is an extended telephone system along a railroad, there should be by all means a thoroughly competent telephone transmission engineer who can lay out the circuits and see that they are properly connected, so that good transmission will result.

The recent storm has shown the susceptibility of the overhead wire plant to serious damage and interruption of service. Unquestionably, this part of the plant, both among the railroad companies and the telephone companies, must be improved in the near future; but whether it is going to be a case of universal installation of conduits or steel poles or concrete pole lines, is yet to be determined.

Great economies would be possible in the handling of communications, in the handling of railroad trains throughout the country, if there could be some sort of combination or co-operation between the railroad companies and the telegraph and telephone companies. It is easy to see that one conduit line along the railroad tracks between the important cities of the country

would furnish means of communication for all telephone messages and telegraph messages, train dispatching, and the signal line service. If we are looking for economies in the handling of communications, I think that is one very fruitful field that is open to us.

John B. Taylor: One point that I want to raise is the relative ability of the telegraph and the telephone circuits to withstand disturbances from power lines. I ask if in making reply the author will express some opinion upon this subject, as well as upon the relative ability of the two systems to continue service through different atmospheric and wet weather conditions.

In some respects the telegraph has the advantage here, in that it is less sensitive to the extraneous currents, and in other respects the telephone seems to have the advantage, in that there is no definite current above or below which the instrument will operate or become inoperative. The transmitted current may be very small, and still be a good recognizable speech current, while in the telegraph line, if it becomes small, it may entirely fail to actuate the instrument.

W. Lee Campbell: I want especially to call your attention to Mr. Clapp's suggestion that the use of the telephone in railroad service may be extended very much further than most railroad telegraph engineers seem to have contemplated up to date, by the railroads operating their own telephone plants at their terminal headquarters. I know of at least one large railroad which is now commencing this plan, viz: it is buying plants to install at its terminal and division headquarters, and is arranging so that any official, by calling the operator in charge of the message line, can talk direct to any station along the railroad line, and, vice versa, any official who may be out along the line at any station may signal the operator at headquarters and have her call the local official desired and connect the two together. This is something which is only possible, as a rule, where the railroad owns its own plants, because the public telephone companies which rent telephone service object to having any privately owned lines or equipment connected to their systems. I believe there is going to be a very large development along this line, and I believe that it will be a very great factor in converting the telegraph engineers and other railroad officials to the use of the telephone in the place of the telegraph.

M. H. Clapp: Referring to Mr. Maver's statement, in stating as a disadvantage the slowness of the telegraph when discussing a subject over a wire, I imagine that this is largely due to the way one has been trained. I have never discussed many subjects at length over the telegraph, however, I have discussed very satisfactorily many matters over the telephone for long distances. I have always had the impression that the telephone provides a quicker method than the telegraph.

As to the matter of operators cutting in on the circuit, I did not mean to imply they could not cut in and listen on the tele-

phone circuit. The chances are, though, that they do not do this as a general thing, because they cannot attend to other duties if they are cut in on the circuit continuously; in the case of the telegraph instrument, however, they can listen from different points in the room while employed at other work.

As to the matter of saving, I spoke of $100 a month, but I did not mean to imply that this was the only saving; it was given only as an illustration of possible savings. Unfortunately, a great many of the savings made possible by the use of the telephone on a railroad are more or less intangible and hard to express in figures. This $200 I mentioned is an illustration of the tangible saving which we figured out in a special case.

Referring to Mr. Harkness's statement on the advantage in flexibility of the telegraph over the telephone, I had more inmind circuitous routings rather than any condition on the division. I appreciate very thoroughly that, by having a large number, or a reasonable number, of telephone circuits on a division, the system can be made practically as flexible as the telegraph.

I also appreciate that selectors have been used very successfully on telegraph circuits. However, they do not appear to be so generally in use—at least it would seem that the telephone had so many advantages over a telegraph circuit with selectors, that their use in connection with the telegraph has not been considered except in a few cases.

Referring to Mr. Hill's statement, comparing No. 9 copper with No. 8 iron, I appreciate that possibly I did not carry that comparison to a logical conclusion when considering the telegraph superimposed upon the telephone circuit. In my reference to the necessity of a special telephone circuit for the use of employees along the line, I had this more in mind: Where the booths or cabinets in which telephones are placed are being used very frequently, and are stationed every half mile or so, I do not believe it good practise to provide means (even with a switch) of cutting in a telephone on a dispatching circuit. It would no doubt be better to provide separate circuits and terminate the circuits in various private branch exchanges along the line.

Referring to the use of the automatic system on the railroads, I believe that it is entirely practicable, especially in shops and terminals, where the number of telephones that do not need outside connection is large. There is one disadvantage, as I see it, however, in placing the automatic system in general use on the railroad—it is pretty hard to arrange a plan for connecting the long-distance lines to the automatic line.

Relative to power line disturbances affecting the telegraph and telephone, it has been my experience that power lines, electric light lines for example, affect the telephone a great deal more than they do the telegraph. In some cases it requires special study in order to avoid the inductive disturbances.

W. Lee Campbell (by letter): Mr. Clapp infers in his response to the discussion of his very interesting paper that there is

some difficulty in the way of connecting automatic intercommunicating systems installed in railway terminal headquarters with long-distance telephone lines, or railroad message telephone circuits. I am somewhat at a loss to understand whether Mr. Clapp meant by this that the Bell Company, heretofore, has objected to connections between its long-distance lines and either automatic or manual switchboards owned by others, or whether, not being thoroughly familiar with automatic apparatus, he is under the impression that it is more difficult to connect it to long-distance lines or message lines than it is to connect manual switchboards to such lines. Since some members of the Institute may place the latter construction on his remark, I wish, in justice to the manufacturers and users of automatic switchboards, to make it perfectly clear that such switchboards can be and have been, for many years, connected to long-distance lines just as readily as manual switchboards have been. Calls from automatic switchboards to long-distance lines and vice versa are made by the thousands every day.

Donald McNicol (by letter): In view of the title selected for Mr. Clapp's paper, I take it, that, in the main, its scope is intended to include only a comparison of the telegraph with the telephone as a means of dispatching railroad trains, and as a medium of communication between railroad officials and operatives for the purposes of train operation.

The extensive employment of the telephone for the purposes cited, during the past eight or nine years, furnishes conclusive evidence that the telephone method more satisfactorily meets general railway requirements.

The points I wish to touch upon relate to the so-called "message" circuits, and to the efficient operation and maintenance of telegraph lines and equipment, with the object in view of increasing the usefulness of the telegraph.

It is quite possible that the general application of the telephone to take care of the service for which it is best adapted, has diverted attention from the possibilities in the way of increased efficiency of the telegraph.

It is stated in the paper that telegraph operators are scarcer now than formerly, and that the grade of men in this service is below that of the men engaged in the work a few years ago. My understanding is that the available supply of telegraphers has been, during recent years, considerably above the demand, and so far as ability is concerned, it is well known that the average telegrapher today can handle at least 25 per cent more messages per hour than were handled by the average telegrapher of a decade or two ago. It is further stated in the paper that the opportunities which the present-day telegrapher has to enter other fields of activity are much more frequent than 20 or 30 years ago. With reference to the situation here presented, I believe that it is very rarely now, that a telegrapher has an opportunity to get into any other electrical industry, due to the fact that speciali-

zation has rendered him unfit for any but the very low salaried places, such as "helper" or as student, and also to the fact that universities and colleges are turning out thousands of trained applicants for positions in the electrical field. Twenty years ago the heads of most electrical enterprises of any importance were ex-telegraphers, and the telegraph was the most prolific school of engineering. While the present outlook is rather forbidding to the telegrapher, it is very favorable to the telegraph, as it is now possible permanently to avail of the services of the brightest men who enter the service—those who formerly left it after becoming good electricians.

It is also stated that the number of messages that can be handled on a telephone message-circuit will average twice the number that can be handled by telegraph between the same offices. My opinion is that the reverse of this would be nearer correct—even where plain language messages are concerned. In the transmission of code telegrams, telephone handling is practically out of the question. A first-class telegrapher can handle seventy telegrams per hour all day, without hardship, on circuits practically unlimited in length. Telephone message work that I have seen done on comparatively short circuits and under very favorable circumstances, fell far below this figure in performance.

Again, it is stated that as compared with the telegraph, the telephone is a great time-saver, due to the fact that a dispatcher can transmit orders faster by telephone. It is my impression that where train orders are copied by pencil or stylus, the dispatcher generally can transmit by telegraph considerably faster than most operators can form copy sufficiently legible for trainmen to read. This brings to notice the fact that the speed of transmission in either case is determined by the speed at which the person receiving the order can write it down legibly. Undoubtedly a skilled telegrapher can write more rapidly than a trainman or an untrained clerk. These considerations emphasize the fact that the alleged greater speed of the telephone than that of the telegraph, where written messages or orders are concerned, is of no evident advantage.

Certainly, the telephone is a more satisfactory medium for carrying on short-distance conversations, especially between non-telegraphers, and the personal contact through the agency of the voice aids materially in limiting the discord resulting from misunderstanding of intent and attitude, which seems to be inseparable from the activities of train operation.

The paper states that under certain conditions the telegraph circuit is susceptible to disturbances to a greater degree than is the telephone. I ask Mr. Clapp if in this case a metallic circuit telephone line is being compared with a grounded circuit telegraph line.

In recounting the "disadvantages" of the telephone, I see no mention made of the fact that where telephones are used for train wire work, the operator has to remain at his desk with the

receiver to his ear in order to be informed of what is going on, while with telegraph operation, the operator may keep in touch with what is passing over the wire while attending to other duties, and without having to remain near the instrument.

Mr. Clapp says that except in very few cases the telegraph lines and equipment on railroads are not maintained at as high a degree of efficiency as are the telephone wires and apparatus. It is also stated that "the telegraph will probably continue to handle messages for the long distances, such as 500, 1000, or 1500 miles, for a considerable time to come." Those in close touch with the entire subject will undoubtedly agree that this latter conclusion is well founded, notwithstanding that a number of expensive attempts have been made to employ the telephone for this very purpose.

With reference to careless maintenance of telegraph lines and apparatus, it is my belief that herein are great possibilities for betterment, involving a reduced cost per message handled and a faster service. The railroad companies have in many instances availed unstintingly of expert telephone advice, in which they have been industriously assisted by the telephone companies, while the telegraph, even for long-distance work, has been regarded as a necessary evil—something to be dispensed with, no matter what takes its place.

It occurs to me that where there are five million telegrams per year handled on one railroad, with little likelihood of the number per year decreasing as time goes on, the possibility of clipping off half a cent per message in the cost of handling, by increasing the efficiency of the telegraph, should prove an alluring prospect in these days of high aims.

M. H. Clapp (by letter): Referring to the discussion submitted by Mr. McNicol, I think the points made by him are very interesting and some of them are well taken. I believe that there is a great deal in the idea that in our desire to extend the application of the telephone to the railroads, we have overlooked possibilities in connection with the telegraph. However, I believe at the present time more and more attention is being given to the development of the telegraph, especially to automatic telegraphy.

It is difficult for me to agree with the assertion that the available supply of operators has been sufficient during the past few years. There has certainly not been an adequate supply in the Northwest during this period. Of course, at the present time there is very little, if any, trouble experienced in obtaining operators. However, we consider that at present, to say the least, we are not having prosperous times. As soon as business conditions improve, I think we will have serious difficulty in obtaining operators necessary to handle our business.

Relative to the ability of the operators of today, I appreciate that first-class operators can, by the aid of the typewriter and other modern equipment, handle more messages per hour than

was formerly done under less favorable circumstances. However, it has been our experience, and the experience of other railroads in the West, that the average operator is not as competent as formerly.

Mr. McNicol apparently misunderstands the point that I was endeavoring to make in connection with the opportunities for the telegraphers to enter fields other than the telegraph. I made the statement*: "Twenty or thirty years ago . . . . . there were not then the many opportunities to enter electrical pursuits that there are today." In this I was endeavoring to call attention to the fact that two or three decades ago the electrical field was very much limited as compared with the conditions of today for the man who desired to take up electrical work, and that the studying and taking up of telegraphy was one of the few opportunities in this line of work, instead of one of many as is the case today. The result of this condition was that a great many high-grade men entered the telegraph field, and as stated by Mr. McNicol, "twenty years ago the heads of most electrical enterprises of any importance were ex-telegraphers." Also, a considerable number of these men who started telegraphing in the early days rose to important positions in connection with the different railroad companies in this country. I agree entirely with the statement that under present conditions it is difficult for a telegrapher to change to another line of work. However, this does not change the condition that formerly the telegrapher on the railroads was a higher grade man than at present, and, even if he did leave the railroad, the railroad had the benefit of his services while he continued on the system.

The statement is made that operators can send without hardship seventy messages per hour. This may be true in commercial offices in connection with bonus wires and where the messages are short, as compared with those handled on a railroad. In our offices an average of thirty messages per hour is a high one. This is on the basis of handling the messages as they are offered and includes forms, which constitute a considerable percentage of railroad work. Considering now the matter of telephone message circuits, I have watched the operation of several of these circuits and I have yet to find a case where the number of messages handled was not practically double the number handled on the same division or section of line that was formerly handled by telegraph. This statement applies almost exclusively to local or way circuits on railroad divisions, and it is only fair to say that the ability to call in promptly the different way offices along the line is a very important factor in favor of the telephone.

The saving of time in the transmitting of train orders by telephone, as compared with the telegraph, is not in the sending but in the repeating back of the orders. The same order is

*See page 328 of this volume.

often given to five or six operators at the same time. Now, it is necessary to have the order repeated back by each operator receiving it. When this is done by means of the telegraph, the order cannot be repeated back by the operators any faster than they can send over the telegraph wire. On the other hand, the operators on a telephone circuit can repeat the order back as fast as they can read it and the dispatcher can underline the words in his order book. Further, in connection with the speed of receiving messages over the telephone, I desire to say that messages can be received by telephone on a typewriter by an expert typist much faster than can be done by the telegraph unless code is used, which would not be practicable in connection with an average railroad office.

In reference to the condition under which telegraph circuits are more susceptible to disturbances than telephone circuits, I had in mind grounded telegraph and metallic telephone circuits. I appreciate that if metallic telegraph circuits were used some of the statements made in my paper in comparing the telegraph and the telephone would not hold true.

The disadvantage in the use of the telephone mentioned by Mr. McNicol, of the operator being obliged to remain at his desk with the receiver at his ear in order to be informed as to what is taking place on the circuit, is really negligible and is not considered by the railroads, except in a few special cases. It is very easy for the operator to cut in on the dispatcher's circuit and ask the dispatcher any question desired. In many cases the operator can, by using judgment, ask questions and obtain answers when the dispatcher is talking to another operator on the line, and not cause any perceptible interruption to the operation of the circuit. Also, in practise the operator really has more freedom when the telephone is used than is the case with the telegraph, for in connection with the former he does not have to be listening for his call on the wire and can work outside of his office, or at any point in the station, as long as he is within hearing distance of the telephone bell.

There is no question that the reduction in the cost of the handling of telegraph messages by half a cent per message would be a very profitable matter to consider by any railroad company. However, I desire to call attention to the fact that on a railroad there is not the same opportunity for cutting down the cost per message that is possible in connection with a commercial telegraph company, for the reason that railroad messages are handled in many cases by operators and agents who have a great many other duties to perform, telegraphing being merely incidental to other work. There are only a few offices handling enough messages and having enough operators so that economies can be effected in handling the business. The five million messages per annum to which I referred in my paper were handled by some 1250 operators.

Presented at the Cleveland Section Meeting of the American Institute of Electrical Engineers, Cleveland, Ohio, March 23, 1914.

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SIXTY-CYCLE SYNCHRONOUS CONVERTERS

BY L. P. CRECELIUS

ABSTRACT OF PAPER

The paper describes some 60-cycle, six-phase, 600-volt, synchronous converters used in railway substations in the suburbs of Cleveland. The advantages of the use of 60-cycle apparatus include standardization of frequency, low cost and high efficiency. The converters are of the commutating pole type and a number of special features of their design are described. The improvement of commutation due to commutating poles makes it possible to use fewer poles and higher armature speed, but this has the objection of increasing the noise, which would have been objectionable in neighborhoods where these machines were used. To overcome the noise the armature ends were sealed up and a shield provided behind the front leads, thereby cutting down the ventilation to a considerable extent. The field windings were compounded in order to hold the d-c. voltage constant, and in order to maintain the power factor of the supply circuit at unity the converters were over-excited to produce a leading wattless current sufficient to overcome the reactance drop. In order to overcome the heating effect due to restricted ventilation and over-excitation the value of 3500 amperes per square inch of armature conductor based upon d-c. output at rating was adopted. To permit of a-c. starting the copper dampers are interconnected between the poles to produce a squirrel cage connection all around the field structure. Extracts from the specifications under which these machines were built are appended, as well as extracts from the contract under which the power supplied to the substations is purchased.

ONE year's experience with the successful operation of 15,000 kw. of 60-cycle, six-phase, 600-volt d-c. synchronous converter substation equipment, establishes a precedent for the use of 60-cycle current for purely railway use upon such a scale. This equipment is installed in four substations located in the suburbs of Cleveland.

The fact that only such apparatus that could be depended upon *without question* could be employed to supply efficiently the d-c. power for the railway, required, in the absence of standard practise in the use of 60-cycle converters for this purpose, a very critical and careful consideration on the part of the purchaser, of the essential details of design.

Extracts from the specifications under which the equipment was manufactured are appended, also extracts from the contract

under which the power supply to the substations is purchased. These contracts are correlated in that the former determined the design of the apparatus best suited to take full advantage of the power company's 60-cycle service offered for sale at cost under certain conditions. Both contracts therefore contain some unusual provisions, a few of the more important of which will be briefly alluded to in the following pages.

Synchronous Converters

The introduction of the commutating pole has been extremely beneficial to commutating apparatus, especially in the case of converters. Affording the means of increasing materially the output per pole, it has caused a corresponding reduction of the number of poles per machine, thus providing a marked improvement in the mechanical design of the 60-cycle converter. More latitude in the width of pole face and spacing of brushes has been secured, thereby working towards the mitigation of the disastrous consequences of flash-overs.

The commutating pole, by reason of its rectifying influence upon the armature conductors at the instant of commutation, has also been the means whereby, at the same time, good commutation is secured at the higher speed resulting from the use of fewer poles. This increase in speed, however, has one serious objection from an operating standpoint, viz., noise. In addition to such noises (current and magnetic) as are inherent in all machines irrespective of speed, and are not especially objectionable, there must be included windage and brush chatter, which increase at a tremendous rate with speed. The operation of several machines, such as those under discussion, in one station, without compensating for this, is simply out of the question, as the sounding of alarms and ringing of telltale bells cannot be heard. Besides having a detrimental effect upon the nervous system of the operators, the noise would soon be declared a public nuisance in the neighborhood. By far the most objectionable portion of the noise is due to high-pitched windage tones, and these have been practically eliminated by sealing up both ends of the armature and providing a shield behind the front leads. Cutting down on ventilation to this extent requires that careful consideration to be given to the size of the armature conductors.

Another important point affecting the temperature of the armature winding is the rapid temperature rise of the conductors lying close to the collector ring taps, which is out of all propor-

tion to that of the balance of the winding when operating converters at less than unity power factor. This heating is not uniformly distributed on either side of the tap, but shifts from one side at leading power factor to the other side with lagging power factor.

It is highly desirable in railway work to hold fairly constant d-c. voltage on converters and the simplest way to do this is to compound the field winding. This has several other incidental advantages, one of which is to lock the converters together through an equalizer switch which holds them in parallel on short circuits, which are frequent upon railway systems. The amount of compounding desired varies with the extent and character of load fluctuations, line drop, etc., but whatever the amount it must be offset with reactance in the supply circuit, and in order to prevent its disturbing influence upon the regulation of the system it must be located at the receiving end of the line. In this case it has been given a low value because of the comparatively steady load and low resistance of the circuit.

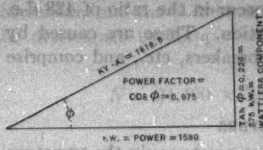

FIG. 1

To maintain the power factor of the supply circuit at unity, as required by the contract [section 9, paragraphs (c) and (d)], calls for over-excitation of the converters to produce a leading wattless current sufficient to overcome the reactance drop. The effect of this is to produce heating in the armature conductors above that caused by the load. When overloading occurs this becomes serious, as may be illustrated as follows:

In Fig. 1 the relations between kilovolt-amperes and kilowatts and wattless component are represented graphically and given the values at which the converters are operated at rating.

Theoretically the ratios between the heating of the winding of a six-phase converter operated as a converter at unity power factor and running as a generator mechanically driven are:

Average value of all coils	0.27 to 1
Coils tapped to slip rings	0.418 to 1

but when the converters are operated at 0.975 power factor as shown in the diagram the heating ratios become:

Average value of all coils	0.313 to 1
Coils tapped to slip rings	0.656 to 1

This means that the average coil has become 15 per cent hotter and the tapped coils 57 per cent hotter at the same load. When overloading to 150 per cent rating these values are:

Average coil $1.15 \times (1.5)^2 = 2.59$ times the heating at 100 per cent load and 100 per cent power factor.

Tapped coil $1.57 \times (1.5)^2 = 3.63$ times the heating at 100 per cent load and 100 per cent power factor.

This indicates the wisdom of holding reactance to low values when unity power factor is essential in the supply circuit. It was due to the imposed limitations of power factor and restricted ventilation that a value of 3500 amperes per square inch of armature conductor based upon d-c. output at rating, was placed in the specification.

The provision relating to flux density indicates the purchaser's desire to have considerable generator capacity in the machines to drag through short circuits on the d-c. side. On the railway system in question, short circuits occur in the ratio of 428 d-c. to five a-c. per annum per substation. These are caused by falling trolley wires, cars opening breakers, etc., and comprise a factor to be reckoned with.

Field Dampers

To permit of a-c. starting with low reactance in the armature and the main field poles fully equipped with pure copper dampers, it is necessary to interconnect or bridge the dampers between poles, to produce a squirrel cage connection all around the field structure. This bridging of gaps between poles causes the commutating pole to become surrounded by the field damper circuit, and seems objectionable because of the possibility of making this field sluggish to load changes. Although this has undoubtedly some slight influence upon the sensitiveness of the commutating pole, it is not noticeable in practise. The fact is that a low-resistance field damper circuit of pure copper grids is far superior to any other arrangement, as several combinations of open and bridged damper circuits of various resistances were tried.

A much-debated question has been the effect of commutating poles upon converters at times of hunting, and it may not be out of place here to record the behavior of these machines when running from turbine-driven and engine-driven prime movers. The power supply is generated by turbine-driven generators and no hunting takes place, but several times for short intervals engine-driven genera-

tors were paralleled with the turbines and the operation of the converters carefully observed. Instantly a wild hunting is set up, the pulsations of which agree in frequency with the speed of the engines, viz., 100 rev. per min., accompanied by violent sparking at the brushes at very light loads, and flash-over takes place at about full load. Thus at any stage the operation is absolutely unsatisfactory. Upon the same generators may be operated, without much trouble in this respect, other synchronous apparatus, including low-voltage converters without commutating poles, although the pulsations from the engines are distinctly noticeable at these machines. It is not at all unlikely that the heavy resulting armature reaction at times of hunting reverses the polarity of the commutating pole, thus becoming the means of exaggerating very much the tendency to flash-over.

In this connection it is interesting to note the agreement between the natural or characteristic period of oscillation of the converters and the pulsations of the supply circuit. This may be determined by Kapp's formula* as follows:

$$N = 24{,}400 \times \sqrt{\frac{P \times p}{Wr^2 \times S \times \theta}}$$

in which

N = natural period in swings per minute
S = revolutions per minute
P = rated output in kw.
Wr^2 = weight in pounds of rotating element times (radius of gyration)^2 in feet.
p = number of poles.
θ = the angle in degrees whose sine is full-load a-c. current divided by a-c. short-circuit current.

Substituting values in this equation we have $N = 90$, which serves to explain that the characteristics of the machines are such as to make them inherently sensitive to pulsations ranging from 90/1.4 to 90/0.7 per minute. The engine speed noted above lies within these values. But notwithstanding this close agreement the fact is, that commutating poles undoubtedly work against converters operating on a-c. circuits subjected to pulsations or frequent and periodic disturbances, and bar from consideration the use of reciprocating units at customary speeds

*Modified formula by Kapp published in *Electrotechnische Zeitschrift*, 1899.

in connection with 600-volt, 60-cycle converters, for this pole is necessary, as pointed out above, for mechanical reasons.

Efficiency

Because of reduced ventilation and the liberal use of copper and iron in the electrical and magnetic circuits, the efficiency of the converters is very high; being,

at	50 per cent full load	91.8	per cent
	75 " " " "	94.0	" "
	100 " " " "	95.0	" "
	125 " " " "	95.5	" "
	150 " " " "	95.8	" "
	200 " " " "	95.0	" "

Best efficiency at 194 per cent full load.

These values are test results and include all losses. Sixty-cycle transformers are also very efficient, and in consequence the overall conversion loss is low. For a period of one month the substation efficiency is as follows:

A-c. input to substations	3,986,880 kw-hr.
D-c. output at converters terminals	3,667,930 " "

$$\text{Ratio} = \frac{3{,}667{,}930}{3{,}986{,}880} = 92 \text{ per cent}$$

This experience in the use of 60-cycle, 600-volt synchronous converters in railway work may be summed up as follows:

1. Pulsations in a-c. supply circuit must be entirely eliminated.
2. The design must include, in addition to the commutating pole, liberal proportions of iron and copper, notwithstanding the high speed.
3. Field dampers must be very low in resistance and bridged to permit of a-c. starting.

The advantages accompanying the use of 60-cycle apparatus are apparent to all and include, briefly, standardization of frequency, low cost and high efficiency.

APPENDIX I.

Extracts from agreement between The Cleveland Electric Illuminating Company and The Cleveland Railway Company, March 29, 1912.

For the purpose of this paper it is only necessary to call attention to paragraphs (c) and (d) of section nine, relating to power factor. This provision imposes a limitation upon the design of

a compound-wound synchronous converter of considerable importance in affecting heating in the armature winding, and consequently the capacity under which standard converters are customarily rated would be much impaired when operated so as to maintain 100 per cent power factor at the primary terminals of the transformers.

Section Nine

Paragraph (c)—The Railway Company guarantees that the monthly average power factor at each of the Power Company's supply stations shall be maintained at not less than 90 per cent and it is mutually agreed that if the monthly average power factor at any supply station differs from 90 per cent in any month, then the demand for that month shall be corrected and determined in accordance with the following formula:

Kilowatt demand is measured, divided by average power factor of load, and multiplied by guaranteed power factor of load: And that the demand on each station shall be increased or reduced accordingly, before computing the aggregate demand.

Paragraph (d)—The average monthly power factor shall be determined from the ratio of the sums and differences of the groups of single-phase watt-hour meters installed on each supply circuit, in accordance with the formula, $\frac{W'-W''}{W'+W''} \times 1.732 =$ tangent of average monthly angle of lag, from which both the angle of lag and its cosine, which is the power factor, will be determined.

APPENDIX II.

Extracts from Specifications of Substation Equipment

General Information.

The substations (in which the equipment specified below is to be installed) will be located in residential districts of the city of Cleveland and neighboring suburbs, as follows:

* * * * * * * * * * * * *

Capacity of Substations.

1. Windermere Substation, three 1500-kw. units as specified hereinafter.

2. Harvard Ave. Substation, three 1500-kw. units as specified hereinafter.

3. West 117th St. Substation, three 1500-kw. units as specified hereinafter.

4. West 25th St. Substation, two 1000-kw. units as specified hereinafter.

Equipment:

The contractor shall furnish, deliver and erect complete in every respect on the purchaser's foundations and ready for use when connected to the purchaser's switching devices, cables and connections:

Nine 1500-kw., 514-rev. per min., six-phase, 14-pole, 600-volt d-c. compound-wound, 60-cycle, synchronous converters, equipped with commutating poles, mounted on self-contained bed plates, including the necessary single-phase, air-blast type static transformers, all in accordance with the following specifications.

Two 1000-kw., 600-rev. per min., six-phase, 12-pole, 600-volt d-c. compound-wound, 60-cycle, synchronous converters equipped with commutating poles, mounted on self-contained bed plates, including the necessary single-phase air-blast transformers, all to be in accordance with the following specifications.

Armatures:

The ventilating ducts, and the general construction of the spider and fixtures, shall be designed with the object in view of minimizing all unnecessary noise such as vibrations, humming and high-pitched windage tones. The converter station in every case will be located in an important residential section of the city where all such noise must be avoided.

The grouping of armature coils per slot in the armature winding shall consist of such an arrangement that the average voltage between adjacent commutator bars shall in no case be less than 13.3 volts, nor more than 14.3 volts.

Equalizer taps shall be brought out from the end of at least every other armature coil and interconnected with all other coils of the same potential, to provide a thorough balance throughout the armature.

The commutators must have the mica slotted or grooved out to a depth well below the surface of the commutator bars.

The d-c. brushes of all converters must be equipped with a suitable brush-raising device to permit of lifting the brushes from the commutator while starting the converters from $\frac{1}{3}$–$\frac{2}{3}$ full-voltage connections, to be provided in the secondary circuit of the transformers.

Field Dampers:

Only the main field poles shall be provided with heavy copper field dampers, properly arranged to provide full damping effect

to the main fields without disturbing in the least the sensitiveness of the commutating pole, in order to provide for the best possible operating characteristics.

Collector Rings:

Because of the high speed, the collector rings shall be equipped with composition copper brushes and suitable pig-tail connections, instead of the laminated type of collector ring brush ordinarily used in the past.

Current and Flux Densities in Armatures:

The current density in the conductors comprising the armature winding must not exceed an average of 3500 amperes per square inch, based upon d-c. output at rating, *i.e.*, considered as d-c. generator.

The flux density in the teeth of the armature core shall not exceed 130,000 lines per square inch, and the density in the core shall not exceed 65,000 lines per square inch, based upon d-c. output at rating.

The current density per square inch of brush surface must not exceed 42.5 amperes at rating.

D-C. Voltage Regulation:

All the converters herein specified shall be compound-wound with sufficient series field effect to produce only approximately constant 600-volt direct-current voltage. The reactance to be provided in the transformer shall be approximately 8 per cent in order to provide for a total reactance of 12.5 per cent, including converter, transformer and leads.

Performance:

After a run of 12 hours at full load at 600 volts, d-c., the temperature rise of the different parts of the converter shall not exceed the following:

Armature	35 deg. cent. rise by thermometer.
Fields	35 " " " " "
Commutator and collector rings	35 " " " " "

With the load then increased to 50 per cent overload (150 per cent rating) at 600 volts d-c. for two hours, the temperature rise of the different parts of the converter shall not exceed the following:

Armature	55 deg. cent. rise by thermometer.
Commutator and collector rings	55 " " " " "

The above shall be based upon a power factor ranging from not less than 0.98 leading or lagging to 1.00, and on 25 deg. cent. for the temperature of the surrounding air and normal conditions of ventilation. In the event of the temperature of the surrounding air differing from 25 deg. cent. the observed rise in temperature will be corrected by ½ per cent of each degree cent. that the temperature of the surrounding air differs from 25 deg. cent.

Insulation Test.

A test to determine the value of the insulation will be made after the converters have been erected by the contractor on the premises of the purchaser, as follows:

The insulation between core and armature conductors must withstand successfully, a test of 2000 volts at 60 cycles, for 60 seconds. The insulation between the frame of the converter and the shunt field circuit must withstand successfully a test of 5000 volts at 60 cycles for 60 seconds.

Efficiency:

The efficiency of both the 1000-kw. and 1500-kw. converters shall be as follows:

150 per cent of rating	(50 per cent above full load)	95.7 per cent
125 " " " "	(25 " " " " ")	95.0 per cent
100 " " " "	(full load)	94.5 per cent
75 " " " "	(25 per cent less than full load)	93.0 per cent
50 " " " "	(50 " " " " " ")	90.5 per cent

In testing for efficiency all losses including those in the brushes in commutator and collector ring will be taken into account.

Flash-over Test:

The synchronous converters to be supplied under this contract will be subjected to the following test to determine their freedom from the tendency to flash over. Starting at no load, 100 per cent overload (two times rating) will be thrown on instantly by means of a storage battery and the converter must withstand this test satisfactorily without hunting, destructive sparking, or flash-over. Likewise, beginning with 100 per cent overload (two times rating) the d-c. current breaker will be tripped and the load instantly removed. Under this circumstance the same performance with respect to hunting and commutation as above, will be required.

Fittings and Supplies:

Each and every synchronous converter shall be equipped with:

One end-play device (oscillator), d-c. end converter.

One speed-limiting device, a-c. end converter.

One equalizer switch mounted on panel fastened to converter frame.

One suitable shunt field break-up switch fastened to converter frame.

One suitable inductive shunt for commutating-pole field circuit.

One suitable non-inductive adjustable shunt for commutating-pole field circuit.

All necessary leads from brush terminals to equalizer switch and to suitable terminal block, must be provided, including attachments for connecting in shunts and field terminals.

The collector ring brush collars and all studs on switches and terminal blocks, shall be equipped with terminals.

One shunt field rheostat box with terminal dial.

All the supplies and fittings supplied with each converter must be approved by the purchaser's engineer.

Transformers:

The contract or shall furnish, deliver and erect complete in every respect on the purchaser's foundations, and ready for use when connected to the purchaser's switching devices, cables and appliances, seven single-phase, air-blast shell-type, 60-cycle, 11,000-volt primary voltage, 365-kv-a. transformers.

The contractor shall furnish, deliver and erect complete in every respect on the purchaser's foundations and ready for use when connected to the purchaser's switches, cables and appliances, 28 550-kv-a., shell-type, air-blast, single-phase, 60-cycle transformers, 11,000-volt primary winding.

The primary circuit of all transformers shall be arranged for delta connection and each provided with four 2.5 voltage taps. The secondary circuits of the transformers shall be suitable for diametral six-phase connections for the converters, and each transformer secondary circuit must be provided with $\frac{1}{3}$ and $\frac{2}{3}$ voltage taps for starting the converter.

The outside connections of the primary circuits must be extended by means of suitable leads to terminals in the bottom of the transformer case. All secondary taps shall end in terminals brought to the bottom of each transformer, the whole to make a neat and substantial arrangement for bottom connections.

One transformer of each size will be used as a spare unit and provision for its reception will be made in the substations.

Efficiency and Temperature:

The efficiency and temperature of the transformers shall be in accordance with the best modern practise in respect to the type offered.

Secondary Voltage:

The voltage of the secondary circuit must be suitable for the converters hereinbefore described, as follows: When these transformers are connected in delta relation by means of the outside primary terminals and connected across an 11,000-volt, three-phase line, the converter d-c. voltage shall be 575 volts with normal shunt field excitation.

Insulation Test:

The insulation between primary and secondary winding and the frames and cores of transformers will be required to withstand successfully a test of the following voltages, after erection:

Primary Windings	Secondary Windings.
22,000 volts, 60 cycles for 60 seconds.	2000 volts, 60 cycles for 60 seconds.

Capacity:

At the capacity specified hereinabove, and with the proper amount of ventilation (which ventilation must be specified by the contractor) the transformers must have sufficient capacity to meet the overload requirements of the converters without excessive or destructive heating.

Reactance:

Approximately 8 per cent of inherent reactance shall be provided in the transformers for the purpose of interposing not over a total amount of 12.5 per cent of reactance in the circuit, including the transformer, leads and converter.

Blowers:

The contractor shall furnish, deliver and erect on the foundations in the substations:

Six three-phase induction motor-driven, directly coupled, steel plate blower sets, of the following capacity: 15,000 cu. ft. of air at one ounce pressure.

Two three-phase induction motor-driven sets same as above, with a capacity of 8000 cu. ft. of air at one ounce pressure.

Two blower sets to be installed in each substation; the smaller units to be supplied for the West 25th St. substation.

With each blower set the contractor shall supply an auto-

starter, and the voltage of the induction motors shall correspond to the voltage of the secondary circuit of the main transformers to which they will be connected by the purchaser.

General:

Great care must be exercised in the designing of the equipment hereinbefore specified, to guard against undue noise. As stated above, it is anticipated that trouble will result from the operation of unnecessarily noisy equipment in the substations, which by necessity must be located in the suburbs of the city of Cleveland.

(The balance of the specifications covering foundations, painting and finishing, patents, guarantees, etc., follows along usual lines.)

Presented at the 293d Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 9, 1914, under the auspices of the Committee on Use of Electricity in Mines.

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MINE DUTY CONTROLLERS

BY HARRISON P. REED

ABSTRACT OF PAPER

The paper is devoted to discussion of the advisable types of control to be used for various mining equipment, particularly in bituminous coal mines. Complexity and theoretical details have been eliminated as far as practicable with the idea of impressing on the reader the need for certain definite features, without going into the theoretical details of these features.

Electric controllers for equipment outside of the mine proper as a rule have to meet different operating conditions than those controllers which are installed underground. The operating conditions are taken up in detail and proper control equipment is suggested to meet these conditions.

The object of the paper is to bring out clearly to the mine operatives the fact that suitable control equipment is just as important as the installation of a suitable motor, and moreover that no motor, however well adapted to the service, will stand up properly if it is not operated with a controller designed and built specifically to meet the existing installation and operating conditions.

THE application of the electric motor to bituminous coal mines has developed so rapidly that there is no section of the industry in which the motor has not been installed. Not only is the application universal, but the use of electricity in coal mines is steadily increasing, principally due to the increased cost of producing steam at the collieries.

The design of satisfactory motor and control equipment for coal mines is a considerable problem, because of the severe operating conditions encountered. The class of attendants usually employed by the mines to maintain electric motors and their accessories, is unskilled, principally because of the location of the mines and the conditions of work. Many changes in help take place for the same reasons, and it is, therefore, difficult to train the attendants and make experts of them. These conditions make it essential that rugged and reliable electrical equipment be installed.

As the use of electricity in the mines has increased, the electric motor for operating mining machinery has been developed much

more rapidly than suitable controlling devices. Only within the past few years have those concerned realized that the selection of a proper controller is as important as the selection of a suitable motor. Too often is the controller given secondary consideration with the result that a good motor may appear to disadvantage, simply because it is not operated with the right control equipment.

At coal mines, motors are used for haulage, hoisting, ventilating, pumping, coal-cutting, tipple or breaker power, drilling, washing, machine shop and blacksmith shop. In the design of electrical equipment for mines, it is necessary to consider carefully the following: explosive dust and gases, continuity of operation, voltage fluctuations and dampness. It is, of course, advisable to install the control apparatus in a locality which is unaffected by sparks or short circuits tending to some derangement of the apparatus. The design, however, must be made so as to minimize leaks to ground, short circuits, etc., which may cause ignition of explosives, of mine gases or of coal dust, with disastrous results. In gaseous mines, arc producers such as circuit breakers, switches and sliding contacts of rheostats must be properly protected, either by breaking the arcs in oil, or by providing explosion-proof cases.

On account of the unskilled attendants in the mines, the electrical equipment receives less than the usual amount of intelligent attention, while on account of the conditions of operation, it should receive more. Much is therefore left to the designing engineer to solve, but on the other hand, much could be done to improve conditions by the employment of a supervising electrical engineer at an attractive salary, whose duty it would be to *see* that better attention is paid to the care and maintenance of the electrical apparatus.

From a safety standpoint, and it is the writer's understanding that we are to follow the slogan "Safety First", the mine ventilating fan is the most important power-driven machine used within the mining district. Absolute continuity of service is necessary during mining operations to remove poisonous and explosive gases and coal dust from the underground workings. Mine fans are not usually installed within the mines, but at the mouths of the shafts. Mine fan service is, perhaps, the hardest duty possible for a commutator type motor. It runs continually at a constant load, and the mere fact that the load is constant prevents the motor from running light and allowing the brushes to polish the commutator.

Fan Motor Control

It is still a debatable question as to whether constant or variable speed mine fan motors should be used. Some claim that the fans should be arranged to operate at a peripheral speed of maximum efficiency. This means constant speed; but nearly everyone agrees that variable speed is practically necessary in the mine fan, except for tunnels, subways and old workings. Opinions differ as to whether it is better to use mechanical or electrical means to vary the speed of the fan. Mechanical speed-changing devices such as Reeves variable-speed drives are used, but the tendency is towards obtaining the speed changes electrically, especially when this can be done economically. Speed control of a direct-current motor is easily and economically accomplished by shunt field regulation. The speed control of an alternating-current motor is quite a different problem. A straight slip-ring induction motor with control by resistance in circuit with the secondary is perhaps the most familiar type in this country, but it is open to serious objection because of the rheostatic losses with resultant low efficiency. The commutating-pole slip ring motor is used but very little on account of the complexity of construction, which arises from the necessity of commutating both primary and secondary windings. The commutating-pole squirrel cage machine is more simple, but hardly suitable because of its starting characteristics. It is most advisable from a safety and economic standpoint to have the motor self-starting after it shuts down due to failure of voltage. With a squirrel cage motor, this is difficult to accomplish because of the flywheel load.

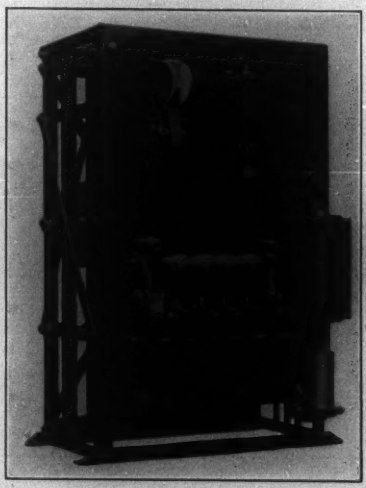
The Sherbius system is one which is used extensively abroad, but the writer understands it has not come into use yet in this country. This system consists of a motor-generator set impressing an adjustable frequency lower than the line frequency on the rotor of the fan motor. This system is exceptionally efficient where the speed reduction is not great. The motor-generator set must have a capacity equal, in percentage of the fan motor capacity, to the speed reduction desired. Thus if 25 per cent speed reduction is required, the motor-generator set must have 25 per cent of the capacity of the fan motor. When a speed below normal is wanted, the motor-generator set is used, while when normal speed is desired, the secondary of the main motor is short-circuited after starting. With the Sherbius method of speed control, the losses are minimized and the efficiency is high.

On account of the possibility of frequent failures of line voltage there must be an attendant continually employed in the fan house or a self-starting controller must be installed. The automatic self-starter should be designed so as to permit the operating speed to be set by a proper authority. When the voltage again comes on the line, after failure, the controller should of itself cause the motor to start and resume the speed it was operating at when the voltage failed. This control has been accomplished very effectually for direct-current motors. The starter is automatic and is governed by a simple snap switch. The starting operation is governed by a pilot solenoid and the shunt field is automatically weakened to an amount corresponding to the setting of the field rheostat lever. An example of this type of control is shown in Fig. 1. The speed-setting field rheostat is shown on the center left-hand side of the board. The controller is equipped with a voltage relay so arranged that when the voltage drops below a predetermined value, the relay drops its plunger, thereby opening a circuit causing all of the starting resistance to be inserted in the armature circuit. The motor then runs at a reduced speed until the voltage again becomes normal, when the voltage relay establishes a control circuit which causes the starting resistance to be cut out, again allowing the motor to run at the proper maximum speed. The reason for re-inserting the starting resistance on low voltage is to guard against "flash-overs" at the motor brushes, when the voltage suddenly jumps back to normal. An overload relay is also provided and is especially recommended for shunt-wound motors. This is connected to momentarily open the motor circuit and prevent "flash-overs" when the line voltage falls abruptly and the motor tends to feed into the line. With compound-wound motors, the overload relay is not essential because the series winding weakens the field when the motor acts as a generator. All of these complications in control could be avoided by the installation of separate feeders for the fan motor, or lines of such capacity as would minimize voltage fluctuations, and it is questionable whether the more or less complicated control is justified under these conditions.

Since moisture and dirt are so prevalent in the locality of coal mines, both the control panel and grid resistance are treated with a special moisture-repelling and insulating compound, corrosive bearings are eliminated and all parts necessarily made of iron or steel are enameled or copper-plated.

[REED]

FIG. 1



[REED]

FIG. 2

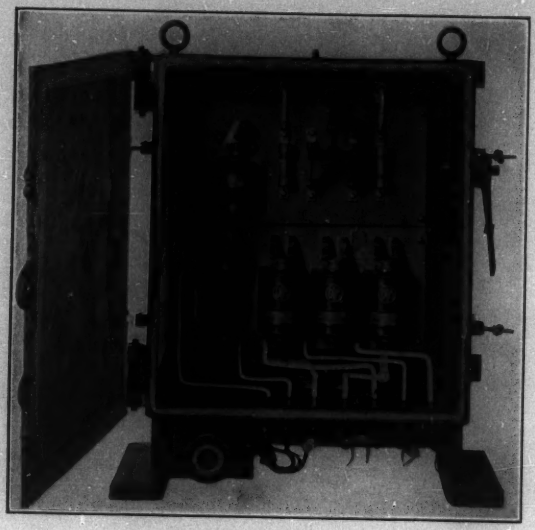


FIG. 3 [REED]

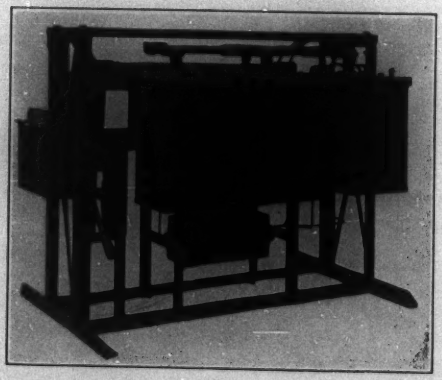
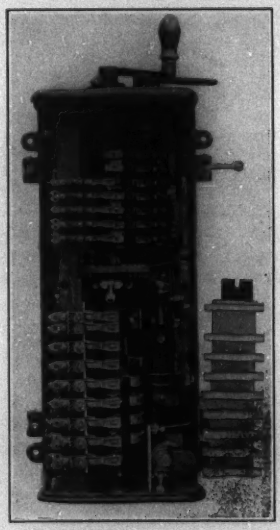


FIG. 4 [REED]

[REED]

FIG. 5



[REED]

FIG. 6

Pump Motor Control

Mine pumps are generally installed directly within the mine, because otherwise the suction head would be prohibitive. The pumps are usually of small capacity and should be operated by a self-starter with a float switch in the sump, or arranged to run continuously. The starter should be designed for automatic acceleration of the pump on resumption after failure of line voltage.

Generally speaking, these pumps are placed some distance from the mine workings and therefore explosion-proof motors and controllers are unnecessary, but it is difficult to design electrical apparatus which will stand up under severe moisture conditions prevalent. A typical pump motor starter for direct current, arranged with a voltage relay for protection of the motor against severe voltage fluctuations, is shown in Fig. 2. The starter is specially designed to guard against corrosion and electrical leakages by using non-corrosive metals and by liberal application of an insulating varnish which helps to prevent short circuits as well as to keep moisture from the iron parts necessarily present for magnetic purposes.

An encased, moisture-proof starter is shown in Fig. 3. This is an equipment especially adapted to installations within the mine, even in locations where arcing is dangerous, because it is equipped with a cast iron case, the cover of which is clamped down on a soft gasket, making the case air-tight. The leads are connected to terminals and a special trough is cast in the enclosing box in which is poured a sealing compound covering the junction of the leads and the terminals. At the right-hand side of the box, facing it, is a handle which closes and opens the service switch. The acceleration of the motor is accomplished by limiting the current peaks with series-wound switches.

It might be well to mention here the rather interesting alternating-current controller shown in Fig. 4. This is a 125-h.p. 2200-volt, three-phase, 60-cycle automatic starter for a slip-ring motor. The starter is "explosion-proof" and is mentioned for this reason. The switches are magnetically operated and the circuits are made and broken under oil. The interior of one of the oil switches is shown in Fig. 5. This controller was installed in the Homestake Mining Co.'s gold mine at Lead, S. D. The outfit starts a pump automatically from a float switch. The control circuit is stepped down to 220 volts so that the float switch does not have to handle the high voltage.

Locomotive Controllers

A subject which is occupying much thought among coal mining engineers is the mine locomotive. The tendency is to eliminate the overhead trolley where there are low ceilings. This may be done either by the use of a trailing cable, kept taut by a tension reel, or by the use of storage battery locomotives. The trailing cable was not very popular until the automatic motor-driven cable take-up was developed. Without this device the dragging cable was always in the way. The motor driving the cable take-up is connected across the line in series with a step of resistance. When the cable is to be hauled in, the motor winds it up, and when paying out is required the cable overhauls the motor.

On account of the difficulties attending the use of trailing cables, it would seem that the coming mine locomotive, when not in main entries, will be operated from a storage battery carried on the locomotive. The present trouble with storage battery locomotives is the necessity of laying them up for charging or of having two sets of batteries and charging them at intervals. The battery must be carefully watched and attended. If the batteries could be automatically charged without delay, the usefulness and reliability of the storage battery locomotive would be materially increased. This may be accomplished by the use of an automatic reverse-current cutout, so arranged that when the locomotive picks up the trolley, the battery will be automatically put on charge. If, however, the line voltage is for any reason lower than the battery voltage, the battery will be automatically cut off from the line. The same applies when the line voltage fails, so that the battery will not be discharged into the line. In this way the same locomotives may be used for gathering and hauling trips. This will result in the battery frequently receiving a boosting charge. The nickel-iron battery, which seems the most popular for mine locomotive work, will show its maximum efficiency when so charged.

Manually operated drum controllers are almost universally used for mine locomotives. These are usually of the series-parallel type and there are two prevailing styles, each of which has its advocates. The first operates the same as a standard street railway drum which has two levers, one reverse and one for accelerating. The other style also has two levers as above, but the reverse lever has two positions each side of the "off" position, one for motors in series and the other for motors in

parallel. This latter scheme is advantageous because it is easier to get straight series only, during gathering.

Rheostatic drum type control is sometimes used for underground haulage engines. A typical drum controller for this service is shown in Fig. 6.

For slope mines, the winding drum for haulage is generally installed in the tipple and whole trips of cars are hauled up at once. These winding or mine haulage machines are usually alternating-current motor-driven with secondary control, either by means of a secondary resistance drum or by means of a liquid rheostat. It is sometimes advantageous to be able to change gears for pulling strings of cars in from the sidings. There has been a tendency of late to put in safety cut-offs so that the current to the motor is interrupted before the cars get to the top. Variable inertia plays an important part in the stopping point, and in fact, the variable stopping point sometimes becomes so annoying that a flyball-governor limit switch in addition to the ordinary limit switch is installed, so connected that if the speed is high the governor allows the first limit switch to trip. If the speed is low, the first limit switch is "shunted" by the governor and the haulage may continue until the second limit switch is engaged.

Hoist Control

A straight vertical hoist is used to a limited extent. Almost invariably this type of hoist can be best electrified by the use of the variable-voltage system, because the hoists are short and therefore acceleration is an important consideration. A flywheel is used to store the energy for acceleration. Even with this arrangement, electrification is in many cases of questionable economic value.

A diagram of an equalizer hoisting set is shown in Fig. 7. The hoist is driven by a shunt-wound, direct-current motor, the motor receiving its energy from a motor-driven generator. The motor-generator set has a heavy flywheel which absorbs energy when the load falls below a certain value and gives up energy when the load is above this value. The speed and direction of rotation is governed by changing the field of the generator. When the generator field is weakened while the motor is in operation, the motor operates as a generator and the generator as a motor, thus delivering energy to the flywheel and giving a dynamic braking effect on the hoisting mechanism. Where an alternating-current motor is used to drive the generator, the liquid rheostat

gives very good regulation. The three phases of the rotor are connected to three stationary plates in separate earthenware pots. Above the stationary plates are connected together three movable plates. These are nearly balanced by an adjustable counterweight, the movement of which is controlled by a small induction motor. The small motor receives its energy from series transformers in the main line of the large induction motor and thus the current in the two motors is proportional.

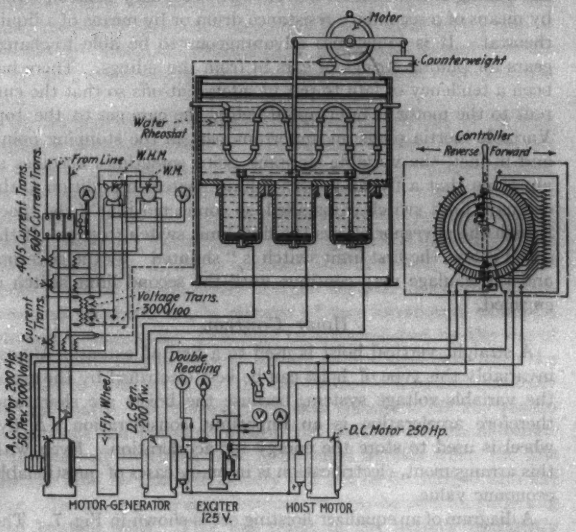


FIG. 7

If the main motor takes more current than it should (depending on the adjustment) the small motor takes more current and raises the counterweight, thereby separating the plates of the liquid rheostat and increasing the resistance in the rotor circuit. This decreases the speed and permits the flyweel to give up some of its stored energy

One case where the efficiency of a vertical hoist was greatly increased by the use of electricity is shown by a change made at the Berwind White Company's mine at Windber, Pa. It was

found impracticable to change the shaft to take care of a larger elevator with more sidings for loading, and an increased capacity of the hoist was necessary because of the increasing production in the mine. A magazine hoist was installed, having a cage with four decks. These decks are loaded by a similar auxiliary cage within the mine. The loading cage is operated by an electric motor and controlled by a simple master switch, so that each of the four decks are brought in succession to the level of the track in the main entry. After the loading cage is full, the cars are run onto corresponding decks of the main magazine hoist and are lifted out of the mine.

Machine Control

Coal-cutting machines are controlled by a plain hand starter fully enclosed. The simpler and more substantial this starter, the better. There is a tendency to design motors for coal cutting which may be thrown directly across the line to start. The writer believes this is a step in the proper direction, because then the control may take the form of a simple hand switch, preferably oil-immersed.

The control of an electric punch or drill is usually a straight hand starter, and the more simple this is, the better.

An important consideration in mine electrical appurtenances is the terminal box. This is used wherever a motor has trailing cables and should be so arranged that putting the plug in the box will close the circuit in oil. An overload should be supplied, which, when it trips, will throw the plug out.

To sum up the situation, mine controllers are just as important as the motors themselves, and the control equipment should receive more thoughtful consideration if our electrical mine installations are to prove successful.

DISCUSSION ON "MINE DUTY CONTROLLERS" (REED), PITTSBURGH, PA., APRIL 9, 1914.

F. L. Stone: There is one line of control on which Mr. Reed has touched very lightly. That is the handling of 2200 volts. This voltage is coming more in use every day, and must be controlled in a safe and efficient manner. The use of oil-immersed switches was the first method tried, but where the operation is frequent and the service severe, as in the case of the mine hoist, either of the slope or shaft type, it does not work out as well as might be hoped. The frequent rupturing of the arc carbonizes the oil, and will eventually cause an arc-over. This comes without any warning to the operator, and usually puts the switch out of commission. Another cause of damage to oil-immersed switches when operated frequently is, that a body of gas will form on top of the oil and finally a hot bubble will arise, and if the proper proportions of air are present a violent explosion will occur, this frequently wrecking the tank, and putting the switch out of commission until repairs can be made. The ordinary oil switch such as is used on a switchboard for control of various circuits may be called upon to operate two or three times a day. A switch to control a hoist operating two trips a minute will operate approximately 1000 times a day in eight hours. In the first case the oil-immersed switch is entirely satisfactory, while in the latter case such information as I have been able to gather seems to indicate that it is entirely unsatisfactory.

The only alternative seems to be a properly designed air-break contactor. Such contactors have been designed, and are on the market, and from everything I can learn are giving satisfactory service. Two of these air-break contactors were installed about one and one-half years ago at the Crow's Nest mine of the Keystone Coal & Coke Company, controlling the primary circuit of a slope hoist of 700 h.p. The operation has been continuous since installation, and even the arcing tips have not as yet been renewed. I have a letter from South America, advising that the air-break contactors are giving most excellent service. One contactor in particular, installed at one of the mines, was put in service early in March, 1912, and at the end of two hundred and forty-four days of operation it had opened the circuit 388,000 times without any renewals or repairs and at a maintenance cost of nil. On the other hand, reports from the same locality on oil-immersed contactors advise that, on account of danger of fire when the oil becomes too much carbonized, it must be renewed every four or five weeks, and between 30 and 40 gallons of oil per switch are required.

From these figures you can readily appreciate that the maintenance of such a switch is a very expensive luxury.

All of the above applies only to switches which are required to operate on a rapid cycle.

Mr. Reed refers to an encased moisture-proof starter to be used in gaseous parts of the mines. I believe it would be better if this casing were built on the principle of the safety lamp, rather than attempt to make it air-tight. Any device of this sort is bound to breathe, that is to say, expel a certain amount of air when warm, and draw in air from the outside when cold. If this action is carried on long enough the quality of the air inside of the box will be the same as that outside, and an explosion might readily be started. Or, when the box is opened for inspection, it will, of course, fill with air from the outside, which may be an explosive mixture. I believe it is generally conceded that it is almost impossible to make a perfectly air-tight joint through which electric wires can be brought. I would like to have an expression of opinion from the Bureau of Mines on this subject.

Mr. Reed in his article makes no detailed reference to control of motors by liquid rheostats. The general trend of the practise seems to be that in motors over 500 h.p. a liquid rheostat should be used for the secondary control. The up-keep of such rheostats should be considerably less than the up-keep of the large contactor panels. The freedom from steps is a very important consideration, and is obtained only in the liquid rheostat. It has been a very difficult problem to design a liquid rheostat with a large ratio of resistance without having the plates so close together that the danger of arcing in event of the motor being reversed is more excessive. This, however, has been accomplished by the use of what virtually amounts to two chambers, one of them of high resistance and the other of low resistance. The low-resistance section is only connected across the slip rings after the motor has attained a considerable speed, and therefore its voltage across collector rings is low. The low-resistance section is cut in by means of a float switch. With such an arrangement the motor could be reversed without any danger of arc-over, as nothing but the high-resistance plates would be in circuit.

Finally, in regard to the part of Mr. Reed's paper referring to mine hoist control, it would seem as though Mr. Reed was of the opinion that a flywheel motor-generator set was extremely efficient. Efficiency is not the aim of the flywheel set, and it should only be used where excessive peaks are penalized or where power station capacity is limited, and it then must be realized that the running of a heavy flywheel throughout the entire day must be done at a considerable expenditure of energy. As a matter of fact, speaking generally, it takes about one and one-half horse-power per ton to operate a flywheel. I will be interested to hear from Mr. Reed as to why he differentiates between shaft hoisting and slope hoisting on the efficiency basis. Personally, I see no difference whatever, except that the control of the shaft hoist is a little more difficult than the control of the slope hoist.

Mr. Reed's statement that the electrification of mine shaft

hoists is of questionable economic value cannot be passed unnoticed. Mr. Reed, of course, would not make such a statement unless he had some figures based on tests and actual observations to back it up. Being particularly interested in mine hoisting, I would deem it a great favor if Mr. Reed would advise us as to just how he arrived at the conclusion that the electrification of mine shaft hoists is of questionable economic value. I have yet to see the case where the shaft hoist has been electrified that it is of questionable economic value.

Sidney G. Vigo: I would like to inquire of Mr. Reed what, in his opinion, is a fair estimate of the largest capacity alternating-current motor that can be applied to a hoist and operated directly on the line of a central station without causing undue disturbance on the system, after taking into consideration the application of the proper controller, as discussed in the paper. This is largely determined, of course, by the size of the station feeding the system, but reference is made particularly to the smaller station, say of 2000 kw., carrying a diversified load. We have had considerable trouble with some of the smaller stations in several instances, by operating motors of 150 horse power directly on the line, using magnetic control. In these cases, faulty regulation of the lighting load was evident.

Graham Bright: High continuity of operation of any apparatus can only be obtained by a constant and systematic inspection. This is particularly true of mine work, since the conditions under which its apparatus has to operate are so very bad and it is difficult to get a good class of operators and inspectors, due to the poor living conditions and isolation of the average mine.

For small pumps up to 20 h.p., the self-starting motor is the best solution of the control problem, as it eliminates the control entirely. If too many motors of this type are placed on a system the first rush of current may prove too much for the generating system, in which case a relay could be provided on some of the motors which would delay their starting for a few seconds so that all motors would not start at once. It seems that the self-starting motor would be a better solution of the problem than the usual control as shown in Figs. 1 and 2. However, where a company has already installed motors that are not of the self-starting type, this control, of course, would be a considerable improvement over the present method of having to cut in and start by hand.

Mr. Reed states that the series and parallel drum controller with the series and parallel feature in the reverse drum is advantageous because it is easier to get straight series only, during gathering. I believe that the straight series position is seldom used, as the motorman will invariably start in multiple. It gives him an easier start, and he can generally start larger loads, since one pair of wheels slipping does not increase the tractive effort of the other pair as would be the case with the motors in series. The real reason for making the series and parallel arrangement on

the reverse drum is on account of the limitation in height. The regular railway type of series parallel controller is too high for mine service, due to the series parallel feature being in the main drum. It has been my experience around the mines that there are few motormen who use the series position very much. The railway type of controller would be a distinct advantage in that the motorman must start in series every time.

I wish to take issue with Mr. Reed regarding his statement that almost invariably the straight vertical type of hoist can be best electrified by the use of the variable-voltage system and that with this arrangement in many cases electrification is of questionable value. It will be found in practise that in a large majority of cases an a-c. wound-rotor induction motor will be used for vertical hoists and will prove the most economical, not only on the basis of first cost but also on cost of operation. Very rapid hoisting, with few or no delays, coupled with restrictions regarding the peak loads that the power company will permit on its system, will only warrant a flywheel equalizer system with voltage control. For very rapid hoisting it is sometimes desirable to use the voltage control system on account of the superiority of the control itself, which readily lends itself to the addition of automatic features. In case the power system can stand the short-time peak loads it is not necessary to use a flywheel, and a synchronous motor-generator set can be used to supply power to the hoist motor. The flywheel and slip regulator losses will be saved and the first cost will be considerably less.

There are no doubt a few isolated cases when it will not pay to electrify a steam-driven hoist, but in the majority of cases a very substantial saving can be made. There are steam hoists in West Virginia at which the cost is over five cents per ton for hoisting from not over 400 feet in depth. Some of these hoists will be electrified in the near future, and it is expected to cut the cost of hoisting to less than one-half of what it is at present.

H. H. Clark: Mr. Stone has asked for a comparison of the explosion-proof qualities of oil switches. The tests that the Bureau of Mines has made have been rather limited in number and have been confined to switches of relatively small capacity. No tests have been made with controllers. The tests were made at 250 volts and with currents no greater than 100 amperes. I have not in mind the exact conditions that surrounded these tests, but about 75,000 breaks were made on each switch while it was surrounded with the most explosive mixture of Pittsburgh natural gas and air. No ignition took place during the tests and it seems reasonable to believe that all switches can be made explosion-proof if the parts are properly proportioned to the service to be taken care of and if the presence of the proper amount of oil in the switch casing can be assured.

From the tests that we have made I cannot say what would happen to an oil controller that is being operated a great many times a minute. It may be that in a comparatively short time the oil level would fall to such an extent that the flash of breaking

the circuit might be exposed and in that case gas would certainly be ignited if it were present. I can say this, however, that in almost every case that we tried it was necessary to renew the contacts several times before the oil level fell to such an extent that the breaking flash was exposed.

H. D. James: Mr. Reed, in the beginning of his paper, makes the following statement:

"Only within the past few years have those concerned realized that the selection of a proper controller is as important as the selection of a suitable motor."

I wish to emphasize this point, as I can recall many personal experiences in which the selection of the motor was such that it was almost impossible to furnish a satisfactory controller. A motor may embody the ideal features for the particular application, but render it very difficult to control this motor in a satisfactory manner. This point has received the attention of both motor and controller engineers with increasingly satisfactory results.

A still further development of the situation has produced the engineer who has the training and experience necessary to study the customer's requirements and select both a motor and controller which will give the best economical results, apart from a purely scientific consideration. This man is commonly known as an application engineer. It is necessary for him to analyze the design characteristics of both the motor and control, and collect the necessary data showing the conditions of load and method of operation that give the best results for the customer. Often the motor can be modified slightly in design, and the controller changed to give a larger output with less strain to the apparatus and decreased power consumption. This is very important from the standpoint of the customer, as the only two items which usually interest him are, first, the amount of capital invested in the apparatus, and second, the cost of power and maintenance.

He is not willing, as a rule, to pay for new and interesting scientific experiments. Occasionally such features have an advertising value, but as a rule, they have no commercial importance. The man who spends most of his time following the design of either motor or control is not usually equipped to make a well balanced application. The electrical industry owes a great deal to the pioneer application engineers, and it is profiting more every year by the increased number of these engineers who are making a special study of each customer's requirements and assisting the customer to solve his power problem so as to get economical operation and increased output.

W. C. Kennedy: In many of these cases, particularly the ones referring to the mine hoists, the equipments are developments, not of the controller alone, but it is a question of the adaptation of the controller, the hoisting machine, and the motor to the conditions of service—a great deal like the ordinary electric-driven elevator. You have to make all three units work together. Sometimes you have to modify the controller

to meet the characteristics of the motor, and sometimes the motor must be modified to meet the characteristics of the controller, and local conditions also affect these different items.

The controller shown in Fig. 1 has been referred to as unsafe for installation in the mine. That controller was discussed under the head of "Fan Motor Control." That is not designed, primarily, to go inside the mine, where it would be subject to explosive gases. In nearly all cases the ventilator fans are mounted at the top, outside, and at the head of the shaft. The main feature of these fans is continuity of service, and to be able to get any speed adjustment desired over a wide range. The amount of air to be delivered varies greatly, depending upon the weather conditions. That controller is designed for use with the shunt-wound motor, having a speed range of about 4 to 1. It is capable of being set to any predetermined point and locked in that position by the mine operator.

The controller shown in Fig. 2 is also not of the enclosed type. It is not so elaborate as the first one, because it is not designed for adjustable-speed motors. It is intended to be used with drainage pumps. These pumps, as I understand it, are located at a point in the mine which is determined by the main operating conditions. They are not usually located down where the cutting is going on, but are mostly on a ventilated shaft, where they obtain the best drainage, and then are connected to the different sumps or drainage wells.

We have built controllers using both air-break switches and the oil-immersed switches, and both types are in satisfactory operation.

The controller shown in Fig. 3 is of the air-break type, tightly enclosed, and I believe operates satisfactorily. We have made some controllers that are not closed as tightly as that, and personally I would be inclined to think this type of control would be better than trying to adapt the principle of the safety lamp. It may be argued that it may collect gas inside, that it is bound to breathe, which is true, but at the same time any electrical device must be inspected, or at least should be inspected, no matter if it is enclosed. There should be a man in every mine, as there is a man in nearly every mill, an inspector, whose duty it is to examine these automatic devices, but I think it would take a long time before that controller could collect an explosive mixture in it.

Mr. Clark has referred to his tests on the oil-break switches, and states that he has tried them up to 75,000 times, and they are still satisfactory. Of course, the ordinary switch will have to operate more than that. We have been very successful with oil-break direct-current apparatus as well as alternating-current apparatus, in situations where there is danger of explosions. This refers to a line of work which is not concerned with mining apparatus, and that is in the powder mill industry. It requires a great number of manually operated controllers, oil-immersed, and they are certainly in a dangerous position

when it comes to the danger of a flash or an explosion, and the only answer I can give is that both types of apparatus are operating satisfactorily.

In regard to the locomotive controllers, I am inclined to believe we would consider series parallel probably better than having the series on one side of the off position and parallel on the other. I think the point which Mr. Reed intended to convey was that we are building both types. Neither of these special controllers is the result of the conceptions and ideas of the designers; they have been cases where we have been called upon to furnish special apparatus, and I know that that drum controller was built at the request of some customer. I think that only goes to show that it would be to the advantage of every one concerned, both the manufacturers and the users, if the mine apparatus could be standardized and made to cover the general requirements, and kept away from these special things as far as possible. That has been done in the Pittsburgh territory among the steel mills, and I know that both manufacturer and user are benefited.

C. J. E. Waxbom: Mr. Reed has mentioned controllers for coal-cutting machines. This is a type of apparatus which is subjected to much abuse in mines. The coal-cutting machines start and stop very often, sometimes under heavy overload, and Mr. Clark suggested the use of oil switches for such starters. Personally I do not believe that oil switches for coal-cutting machines would be practicable, as I am afraid that the carbonizing effect of the oil would be too much. Secondly, I believe that the men around the mine would put in any kind of oil which they found handy.

In order to better the starting apparatus for coal-cutting machines, we have lately devised means whereby a coal-cutting machine is started only once during its operation and then stopped. This is accomplished by means of friction control. The motor is started absolutely under no-load and can be released under no-load. In propelling the coal-cutting machine from place to place, the operator of the machine does not operate the starting box, simply the friction control. In my opinion, that contrivance is one of the simplest and most effective, and I believe one of the most durable, of which we know today. It does away with stopping and starting of the controller, which has been the bugbear of many electricians around the mine.

W. M. Hoen: For fan motor control, alternating-current, a wound-secondary motor is advisable if starting current must be limited. If any great amount of speed reduction is required, and resistance control is used, the loss in resistance is objectionable, but, due to the character of the fan load, this loss will be much less than if the motor were driving a constant torque load. However, its use would be advisable where speed reduction was of rare occurrence.

A squirrel cage motor and its control is the simplest, and as possibly one speed for the majority of mechanical appliances

in mine operation is generally sufficient, a two-speed winding will give good results. The control apparatus can be made simple and the starting characteristics for either speed are suitable for fan operation.

Direct current is usually supplied because of locomotives, and if fan service is supplied from the same source, a separate feeder should be run from the busbars. This would eliminate the greater voltage fluctuation.

If direct current is used for pumping, the majority of the machines will be small, and the proper solution of the control apparatus is to eliminate it and use self-starting motors. They are available in sizes up to 20 h.p. and may be thrown directly across the line.

As to hoist control, drum controllers have been used to a great extent in the past, but with increasing use of magnetic contactors, their increased reliability makes it desirable to use drum controllers only on small, low-voltage hoist motors where the service is intermittent. Except in shafts of very large output and extremely fast work, the induction motor is applicable and can be controlled by contactors when the motors are of average size, and a liquid rheostat can generally be used for the larger motors. This liquid rheostat is very simple, consisting of a number of plates connected to the secondary of the motor, and supported in the upper section in a two-compartment tank. The liquid is a carbonate of soda solution and is kept in constant circulation from the lower to the upper tank by a small centrifugal pump. The level of the liquid in the upper tank compartment which contains the plates, is lowered or raised by means of a hollow weir which is under the hoistman's control. This type has the advantage of simplicity and minimum maintenance.

The voltage control system, as described, is ideal, and is only required where the loads to be hoisted are large, the rope speeds high, and the acceleration and retardation rates very fast. If power conditions limit the permissible peak, a flywheel set with induction motor and liquid regulator as described in paper is proper. If the peaks are not a limiting feature, a synchronous motor-generator set will give all the desirable control features, somewhat decreasing the first cost and the no-load running losses.

Coal cutters were formerly built only for use with direct current, but are now available with induction motors. These can be thrown directly on the line, permitting the use of a single oil switch.

A mine with large power requirements can dispense with direct current except for locomotive operation. This simplifies the control problems and permits oil switches to be used for all control work.

Arthur S. Biesecker: Under "Pump Motor Control," in the last sentence of the first statement is the following: "The starter should be designed for automatic acceleration of the

pump on resumption after failure of line voltage." That, to my mind, is rather a broad statement. I am not very familiar with the bituminous field, but in the anthracite field a very large part of the pumping is now done with centrifugal pumps. If that statement is put in practise, I am afraid that the result would be very unsatisfactory to the operator. If you put an automatic starter of that character on a centrifugal pump, and the power goes off, you lose the water, and then your automatic starter brings your motor up to speed, your runners will run hot, and stick, and then you are in trouble. To my mind that is rather a broad statement.

There are several places around the mines similar to that, where it would be positively dangerous to put on an automatic starter, and the only thing to do when the power goes off, is to let the pump stand still until the pump runner comes back and let him start up the pump again, and see that the conditions are right for starting.

W. C. Kennedy: In regard to the last remark, I think that local conditions would alter that to some extent. I have seen one installation in which a controller, practically of that same nature, was used. It was so arranged that in case the voltage fell below any predetermined point to which it was adjusted the starting resistance was cut back in the circuit, and if the voltage rose again it would automatically accelerate. It was also provided with a feature of control so that, in case of failure of voltage, it would start up again in case power was applied. This controller is in operation, and I have seen the installation at intervals of two or three months, and so far as I know it is all right, but there may be some conditions that would alter that. That pump draws from a sump well about three or four feet below the level of the pump. It pumps against a pressure, I believe, of 20 lb. There is one check valve on the suction line, and I do not believe there is any on the delivery line. So far as the controller manufacturer is concerned, he can make the controller so that it will start up again on the application of power, or not, one way just as easy as another.

The question of acceleration has not been spoken of very much. As usual, there are two types of acceleration, one that is not under the control of the current, and the second is the current-limit acceleration using either series switches or shunt switches with relays. The first is usually known as the constant-time acceleration. We manufacture both types, and under the wide fluctuations of energy which are usually found in mines, we find that the constant-time-element acceleration gives much better results, because the current-limit acceleration is found to give trouble, especially if it is necessary to accelerate a heavy load, with varying voltage, or in case of a variable load. In that case it is practically impossible to use the current-limit acceleration. However, I believe that the voltage condition in mines will gradually improve and that may vary the design of the starters considerably.

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SELF-CONTAINED PORTABLE ELECTRIC MINE LAMPS

BY H. O. SWOBODA

ABSTRACT OF PAPER

The considerable number of mine explosions caused by defects of the Davy safety lamps has encouraged the development of electric lamps. Satisfactory results, however, have been obtained only since the invention of the tungsten lamp, permitting the use of smaller storage batteries.

The general requirements for electric lamps are: absolute safety, uninterrupted production of light for at least one shift, and a foolproof design. Prizes offered by the British Government in 1912 for the best electric lamp, resulted in 197 different constructions being submitted. The first prize was awarded to a German lamp, which since that time has been used with great success all over Europe and which is also being introduced in this country.

The construction of this lamp, consisting of several types for different requirements, and the methods of handling it in actual service, are fully described. Some figures covering repairs and renewals are given.

In concluding, the author mentions the only objection that can be raised against electric portable mine lamps, that they cannot be used as detectors of mine gases, as Davy lamps can, and says that for this purpose devices distinctly separate from the lamp will have to be adopted.

IT IS a well-known fact that a considerable number of mine explosions with their enormous losses of life and property are caused by defects and improper handling of the so-called miner's safety lamps, built on the Davy principle. The Bureau of Mines, for instance, mentions in one of its reports that at least two disasters in this country in 1912 were caused in this manner, killing more than a dozen men, and the Prussian Government states that during the decade from 1902 to 1911 at least 27 per cent of all explosions in the anthracite mines are to be blamed on these lamps. Therefore, it is only natural that attempts to develop a portable *electric* safety lamp were made quite some time ago. Satisfactory results, however, have only been obtained since the carbon filament lamps were superseded by the tungsten lamps. Due to their high economy in current consumption they permit the reduction of the battery to such an extent that the weight and size of the portable lamp does

not prevent the miner any more from moving around freely in performing his duties.

General Requirements

Electric safety lamps must answer the following requirements:

Absolute safety against ignition of mine gases;

Uninterrupted production of a steady and sufficient amount of light for at least one shift;

Absolutely foolproof design.

Besides this, it is essential

To have a simple and durable construction;

To keep the weight at a minimum;

To facilitate the charging and inspecting of the battery.

Safety. Careful experiments conducted by the Bureau of Mines in Pittsburgh and also at Gelsenkirchen, Germany, have shown that the only source of danger in a portable electric lamp is the glowing filament of the incandescent lamp.

Sparks obtained by the breaking and establishing of the electric circuit are not of sufficient strength to ignite mine gases, due to the low voltage and amperage of the batteries used, as long as the maximum short-circuiting current of these batteries does not exceed

100	amperes	for	batteries	with	not	more	than	2.5 volts
85	"	"	"	"	"	"	"	4.0 "
65	"	"	"	"	"	"	"	5.0 "
45	"	"	"	"	"	"	"	6.0 "

Therefore it is not necessary to provide special protection against sparking on the switch and on the connections between battery and lamp.

As the filament under normal conditions is operated in a vacuum and enclosed in a glass bulb, the danger of igniting mine gases exists only in case this bulb is smashed without the filament being broken at the same time, so that the latter continues to glow until it burns out. Several absolutely safe methods can be employed to prevent the filament from glowing after the bulb has been broken, and one method which has been in actual use for a number of years will be described in the course of the paper.

Steady and Sufficient Light. The miners' *old* safety lamps furnish a flickering light of about 0.8 c.p. capacity, which rapidly decreases during the shift to about one-half. This is not sufficient light for the miner to perform his work satisfactorily, and, ac-

cording to the investigations made by Dr. T. Lister of Llewellyn, England, is the principal cause of the special eyesicknesses (miner's nystagmus) with which miners become affected. For this reason it was considered advisable to equip the *electric* mine lamps with incandescent lamps of at least 1.5 c.p.

The only source of electrical energy which will produce this amount of light satisfactorily for at least one shift or approximately ten to twelve hours is the storage battery, primary batteries for such an output being entirely too large for use in portable equipments. Years of development have resulted in fairly satisfactory batteries and it seems, in the present state of the art, that the lead cell, regardless of its weight, on account of its comparatively high voltage and slow drop in voltage while discharging, is the most suitable type.

Foolproof Design. Miners' lamps are exposed to extremely rough handling by inexperienced hands and the least mechanical or electrical weaknesses are liable to result in a failure to supply light. The following are about the most important points which must be observed in a successful lamp:

The lamp must be locked so that the miner absolutely cannot get at any part of the mechanism.

It must burn in any position, even under water, and if dropped on solid material, such as rocks, iron, or cement from a height of several feet, must continue to operate.

The incandescent lamp bulb must be thoroughly protected so that it is almost impossible to break it.

The electrolyte of the battery must not leak out.

That constructions of this character are possible, and in actual use, will be shown later on.

Lamp Designs

During the year 1912 prizes were offered by the British Government for the best portable electric mine lamp and not less than 197 applicants entered into competition and submitted samples. After careful tests extending over several months, the first prize of $3000 was awarded to the makers of the "Ceag" lamp described in this paper. Since this lamp has also been accepted by practically all other European governments and was the first lamp approved by the Bureau of Mines, answering all requirements, and still remains today the only approved *hand* lamp, it might be well to study its construction carefully.

Fig. 1 gives an idea of the general appearance of the lamp.

The incandescent lamp is covered by a heavy glass dome, which is protected by four heavy steel rods held together by a sheet steel roof. A substantial hook is attached to this roof, so that the miner can either stand the lamp on the ground or hang it to a post in the immediate neighborhood of his working place. The bottom part, made of heavy corrugated galvanized sheet steel, contains the storage battery. By turning the upper part on the lower, the miner can turn the light on and off.

The construction of the lamp is easily understood from a section shown in Fig. 2.

The incandescent lamp *l* rests in a socket *n*, which is pressed upward by a spiral spring *o* against another spring *p* between the bulb and glass dome *b*, providing a complete spring support and preventing breakage even with the most severe shocks. Electric connection is established for one pole through the socket

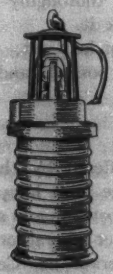

FIG. 1

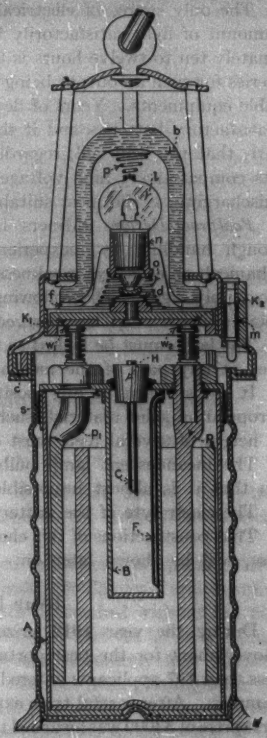

FIG. 2

spring *o*, and for the other pole by another smaller spring *d* inside the socket spring, and insulated from it. In case the bulb breaks, the socket spring pushes the socket upwards, and as the inner spring does not expand as much as the socket spring, the circuit is interrupted.

Lately, another safety device has been added, but is not shown in this illustration. It consists of a fuse, which blows the moment the bulb of the incandescent lamp is broken. This eliminates the possibility of obtaining sparks or getting the filament to glow in case the miner should attempt to push the bulb back into its normal position; it also protects the battery from being short-circuited for any length of time, in case the leads to the bulb have become short-circuited during the accident.

As stated before, the upper part of the lamp turns on the lower part, opening and closing the switch. This rotating movement is limited by a soft iron pin *m*, which acts as a magnetic lock. This pin can be withdrawn in the charging room by a strong electromagnet, and when this is done, the upper and lower parts of the housing separate, and the battery can be removed for charging.

The storage battery consists of a single *round* lead cell with concentric electrodes inside of a celluloid vessel *A* covered with a waterproof lid of the same material. Cylindrical electrodes were given the preference over flat ones, as they are stronger and therefore stand rougher handling. They also warp less, so that in charging, the current density can be increased and the length of time correspondingly decreased. The holes in the terminal sockets contain bushings made of acid-proof metal, into which removable terminals, p_1 and p_2, are fitted. These terminals are pressed upward by the terminal springs W_1 and W_2 against the contact segments K_1 and K_2 of the switch, carrying in this manner the current to the incandescent lamp. Terminals and springs can easily be taken out and cleaned by washing in warm water, a very important point. The use of non-removable springs has been found impractical, as they are very difficult to clean, consequently are liable to corrode and break easily. First-class contact springs, however, are imperative for an uninterrupted light service.

In charging storage batteries gases develop, which must have an opportunity to escape. It is therefore impossible to make the cells airtight. An ordinary opening, on the other hand, would have the disadvantage that the acid would run out, in case a cell were upset, and this would destroy the housing of the lamp. In order to overcome this difficulty, the center of the cell is equipped with a celluloid tubing *B*, which is in communication with the upper part of the cell, where all gases collect, by means of a small side tubing *F*. The gases therefore can pass

from the cell through the side tubing *F* and finally through center tubing *C* into the open, whereas any particles of acid carried along by the gases, will deposit in cylinder *B*. Even if the cell is turned upside down, no acid which may be in cylinder *B*, or any other acid, can escape. In other words, the lamp will burn in any position, without the acid being able to leak out.

The principal dimensions of this lamp are as follows: The weight of the lamp complete is about 5 lb. ($2\frac{1}{4}$ kg.); its height, not including hanger, is $10\frac{1}{2}$ in. (26 cm.); its largest diameter is $3\frac{3}{4}$ in. (9.5 cm.). The incandescent lamp consumes 0.85 amperes at 2 volts. The battery has a capacity of 16 ampere-hours, and the maximum charging current should not exceed 2 amperes. To meet various requirements this standard design is not only made in four different sizes, ranging in weight from $1\frac{1}{2}$ to 5 lb. ($\frac{3}{4}$ to $2\frac{1}{4}$ kg.), but it is also made with two storage battery cells connected in series, resulting for the entire line in capacities ranging from four to sixteen hours of life for one discharge and producing light from 0.75 to 3 c.p.

FIG. 3

Besides this, a number of other modifications have been developed, so that mines can be completely equipped today with electric safety lamps, wherever a permanent wiring in connection with the lighting plant is impossible. Lamps are made for rescue parties, cages, powder magazines, shaft lighting, shaft inspection, loading places, blasting, cars and locomotives (head and tail lamps), etc. A few of these modifications are shown in the illustrations.

The standard lamp, being of the "lighthouse" type, distributes its light uniformly over the entire surroundings. The modification shown in Fig. 3, known as the "trip" lamp, has the incandescent lamp mounted on one side combined with a reflector concentrating the light rays in one direction. This design is mostly used for inspection trips and head and tail lamps for cars and locomotives. It is made in the same capacities as the standard lamp.

The "shaft" lamp illustrated in Fig. 4 is arranged with an adjustable arm, on which the incandescent lamp is mounted, so that the light can be sent in any desired direction. It is made for from 8 to 24 c.p. and from 7 to 12 hours of life for one charge.

FIG. 4 [SWOBODA]

FIG. 5 [SWOBODA]

FIG. 6 [SWOBODA]

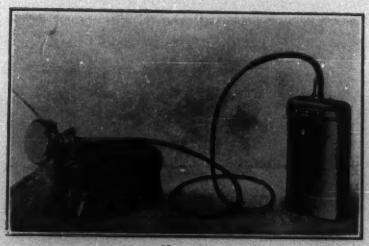

FIG. 7 [SWOBODA]

Fig. 5 represents another type of "shaft" lamp, without an adjustable arm. It is made for 8 and 12 c.p. and for 15 and 10 hours of life for one charge.

The lamp illustrated in Fig. 6 is especially suitable for places in which ordinary illumination is not sufficient. It is made for 8 to 32 c.p. and for a life of 7 to 15 hours for one charge.

The lamps so far described were designed to take the place of the Davy safety lamp, which is in use in gaseous mines all over the world. In this country, however, the designer of electric safety lamps is confronted with another problem besides. In a great many mines the crews have and still use "naked" lamps fastened to their caps. On account of the strict enforcement of the mining regulations in recent years, a great many of these mines have been and will be compelled to substitute safety lamps. It is only logical that the men in these mines clamor for a type of electric lamp which is as near identical as possible with the present form of naked lamp. To meet this demand, electric cap lamps have been developed, the batteries of which are carried by the miner on his belt and are connected to the lamp by a well-protected special flexible cord. This lamp is shown in Fig. 7.

The principles of construction of the cap lamp (see Fig. 8) are identical with those of the hand lamp, besides several new features which have been added. One is that the incandescent lamp is mounted inside a parabolic reflector, the opening of which is closed by a lens, instead of being covered with a glass dome; another is a ball joint, permitting the miner to direct the light rays wherever they are needed. The third feature is embodied in the flexible conductors connecting battery and lamp. In case of an accident, there is a possibility that the two conductors may become short-circuited and therefore red hot, eventually setting the insulation afire, if they are made of copper or similar material. To prevent this a special alloy has been prepared, the melting point of which is considerably below the temperature which is required to ignite insulation or mine gas. Consequently, if a short circuit should take place, the conductors would melt and interrupt the circuit, before there could be a possibility of danger.

From the foregoing description, it can be seen that portable self-contained electric mine lamps of this type have passed the first state of development, and if one considers that more than one hundred thousand are in daily use in Europe, ap-

parently producing excellent results, there is no reason why the adoption of electric mine lamps in this country should not make rapid progress in the immediate future. The question whether hand lamps or cap lamps, or both, should be used, is a mere matter of detail, which will adjust itself. European practise has adopted the hand lamp exclusively; the sentiment in this country, however, seems to be in favor of the cap lamp. Men who continually change their location in performing their duties will prefer the cap lamp, leaving both hands free for action; men who stay at work in the same place most of the time will favor the hand lamp, which can be set aside or hung up in the neighborhood, relieving them from carrying unnecessary weight.

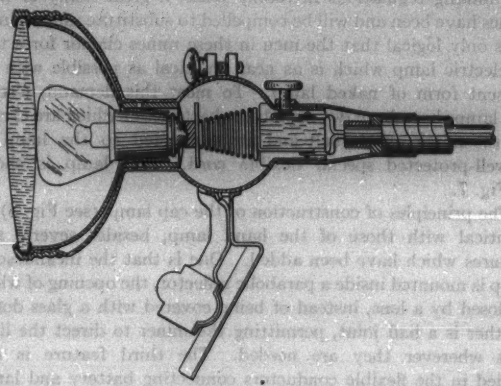

Fig. 8

Lamp Service

When the crew leaves the mine, the lamps have to be delivered to the lamp room for recharging and cleaning. For this purpose the magnetic lock has to be opened, so that the battery can be removed from the housing and placed on the charging rack. The unlocking is accomplished by pushing the lamp lock against the pole pieces of an electromagnet (shown in Fig. 9), which lifts the soft iron pin holding the upper and lower parts of the housing together.

Special charging racks have been designed to receive the batteries. The rack shown in Fig. 10 is intended for 80 cells con-

nected in two series of 40 each. Each circuit is equipped with a switch, ammeter and rheostat, so that the operator can determine the status of the charge at any time. The rheostats are provided with a surplus of resistance, so that less than forty cells in a series can be charged, if necessary. A portable voltmeter with a capacity of about three volts is provided to take the voltage readings on the individual cells. Cells are charged, ready for service, when their voltage reaches a value of 2.6. When more than eighty cells are to be charged, two, three or more racks can be combined, and all the cells can be charged at one time.

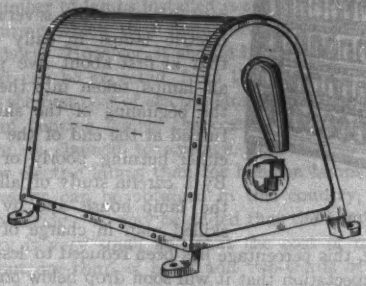

FIG. 9

After the batteries are charged and the contacts and housings have been carefully cleaned, the lamps are reassembled and hung up on special racks, from which the miners remove the lamps, when they begin a new shift.

For mines using a large number of lamps, it is essential that charging, cleaning and repairing be handled systematically and with proper care. For this reason special lamp houses are being erected on the same general principles as those for the Davy safety lamps, but simpler and cheaper, because it is not necessary to make special provision for the safe storage of the fuel, like benzine. The ground plan shown in Fig. 11 represents a lamp house erected for 4000 lamps. It consists of a building about 128 by 33 ft. (39 by 10 m.), containing a charging room with twenty racks, six opening magnets, three small

motors for buffing and cleaning and a small distribution board with a watt-hour meter. To the left of the charging room is the storeroom for receiving the lamps when they are ready for service, and to the right is a small shop for making repairs. Besides this a small room has been provided for a number of benzine lamps, which are being carried for the fire bosses, and on another floor a washroom for the crew.

FIG. 10

Proper care of the lamps has considerable effect on the reliability of the service. One of the large German mines, having several thousand electric lamps in daily use, reports that at first about five per cent of all lamps taken into the mine with the beginning of the shift were returned at the end of the same shift, either burning poorly or not at all. By a careful study of all details in the lamp house and by putting a skilled man in charge of the lamp house work, this percentage has been reduced to less than 1.5, with the expectation that it will soon drop below one per cent. That this last-named figure is not an exception, is verified by

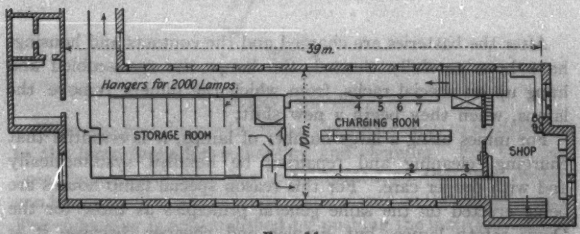

FIG. 11

the Bullcroft Main Colliery Company, Ltd., Doncaster, England. This company has more than 10,000 lamps in daily use and reports the number of defective lamps per shift to be less than one per cent.

The investigation of these defects, if they amount to 1.5 per cent, shows the following:

Defects caused by the incandescent lamps.		
Lamps burning dark	0.6 per cent	
" with broken filaments	0.2 " "	
" " " bulbs	0.2 " "	
Total incandescent lamp defects		1.0 per cent
Defects caused by the batteries		
Batteries leaking	0.1 per cent	
" discharged ahead of time	0.3 " "	
Total battery defects		0.4 " "
Defects due to other causes		0.1 " "
Total number of defective lamps		1.5 per cent

Records covering cost of installing and operating electric mine lamps in this country are not available to any extent, because the number of lamps installed is so far not very large and the time during which they have been in operation is comparatively short. However, it should be possible to form some idea of what can be expected, from the experience in Europe.

Although the first cost of electric lamps is undoubtedly higher than that of benzine lamps, the cost of operation, including maintenance, is claimed to average from ten to fifteen per cent less for electric lamps than for benzine lamps. Whether the same results can be obtained in this country, the future will have to decide. It may be added that the cost of the electrical energy is very small and that the cost of maintenance consists about one-third of labor and two-thirds of renewal of parts, and depreciation.

Especially of importance is the cost of renewing the electrodes of the storage batteries, replacement of complete lamps, which are broken on account of rough handling and accidents, and renewing the incandescent lamps.

The life of the electrodes for lead cells ranges from about 100 to 400 shifts, depending entirely upon the treatment which they receive. At the present time large claims are being made for the alkaline cell, which is supposed to last as long as 2000 shifts. This, however, requires verification by actual tests. Besides this, it must be borne in mind that the higher cost of the alkaline cell, the necessity of using two cells, in series, instead of only one as in the lead battery, and the increase in the renewal of the incandescent lamps, due to the large variation in the voltage, will fully wipe out this apparent advantage. However, the weightiest argument against this claim is the fact that the physical life of mining lamps cannot reach 2000 shifts, as shown

below, and that the natural deterioration of all parts is considerably below this limit.

The replacement of complete lamps which are broken on account of rough handling and accidents undoubtedly varies more or less in accordance with the character of the work performed in the mine. European practise shows that about 0.1 per cent of all lamps per shift are lost in this manner.

The incandescent lamp renewal already has been expressed in figures, in connection with the reliability of service. Excellent results have been obtained, the average life of the lamps being approximately 1000 hours.

From the lamp designs and the lamp service as described above, it can be seen that the development of the portable electric mine lamp has made rapid progress during the last few years, and since, up to this writing, no explosions have occurred wherever installations have been made, it can be said without exaggeration that the electric mine lamp is a success and that it is bound to be adopted more and more.

Of course, as is the case with any new appliance, objections have been raised against the electric mine lamp, especially, because it does not detect inflammable gases as the Davy safety lamp does. There is no doubt that this detail will be overcome in the near future, as there are several principles which can be used for the construction of mine gas detectors. In fact, the German Government only lately has ordered several hundred of these devices, constructed in accordance with the directions of Dr. F. Haber on the acoustic principle and known as "mine gas whistles." These will be distributed to the various mines for a thorough trial.

DISCUSSION ON "SELF-CONTAINED PORTABLE ELECTRIC MINE LAMPS" (SWOBODA), PITTSBURGH, PA., APRIL 9, 1914.

H. H. Clark: The first requirements of portable electric lamps are safety, and the capacity for uninterrupted production of a sufficient amount of light. I wish to emphasize, however, that from the viewpoint of the mine operator, a lamp to be successful must be able to operate day after day with a reasonable amount of repairs and replacement. If this is to be accomplished the lamp battery must be a very sturdy affair. Failure of the battery plates will result in annoying delays and expensive repairs. A dependable battery is indispensable to satisfactory performance.

Another part of the equipment that is most important is the lamp bulb. The cost of replacing the lamp bulbs will be one of the largest items in the cost of maintenance. This cost will be in inverse proportion to the life of the bulb. So far as I have been able to learn, the manufacturers of miniature lamp bulbs have not in the past given much attention to developing the life of the bulb. Up to the present time the demand for battery lamp bulbs has arisen from the extensive use of dry battery flash lamps. The requirements of this class of service are apparently not the same as the requirements of the class of service that we are now discussing. At all events, the life that flash lamp bulbs give has not impressed me as being as long as the users of mine lamps have a right to expect. Reports from abroad lead us to believe that mine lamp bulbs in use there have a life of 500 to 1000 hours, and I presume that no American manufacturer would admit that he could not make as good bulbs as are produced in Europe. The question of bulb life was one of the first problems that the Bureau of Mines took up in connection with its investigation of portable electric mine lamps. The cooperation of bulb manufacturers was sought, and they are now undertaking to ascertain the requirements of mine lamp outfits for the purpose of producing longer-lived bulbs.

Just now the electric cap lamp seems more in demand than the hand lamp for mine service. The cap lamp requires a flexible cord connection between the battery and the head-piece. The design of this cord and method of protecting it from abrasion where it is joined to the battery and to the head-piece is an interesting problem. So far as I am aware, we have no European precedent to guide us in designing this cord because cap lamps have not been developed abroad. I have no doubt, however, that as the result of experience in actual service, that part of the equipment will be developed satisfactorily.

The design of the head-pieces of cap lamps is a matter that should not be overlooked in specifying the requirements of mine lamps. It is important that head-pieces should be designed and constructed so that cord replacements can be readily

made. A most important feature in head-piece design is distribution of light. The light cast should be free from black spots and from sharply contrasting areas of bright and faint illumination, and it is especially desirable that the stream of light thrown out by the reflector should be so broad that shadows are barely discernible on either hand or on the roof or floor.

Mr. Swoboda's paper makes several references to candle power. I should like to ask him whether these figures refer to average candle power over the stream of light, or to measurements made otherwise, and whether with or without a reflector.

Mr. Swoboda mentions an average life of bulbs of 1000 hours. This is a most encouraging and significant statement, and I should be glad to have Mr. Swoboda tell us from what source this information was obtained.

H. H. Smith: It is gratifying to see that the storage battery miners' lamp is finding its place on the programs of technical meetings in this country. It appears from what Mr. Swoboda has said that in Europe they have advanced with the miners' lamp further than we have in America. He has also pointed out that the development has been along quite different lines. The portable lamp which contains the battery within its case offers quite a different problem from that of the lamp used as a head-piece with the battery separate.

I feel that it is necessary to take issue with Mr. Swoboda with reference to his attitude toward the alkaline battery for this class of service. On one of the slides shown on the screen, only a part of which is given in the paper, there was a table of operating costs in which you may have noticed that something over 20 per cent is charged to battery renewals and replacements, and about 35 per cent to attendance; or altogether more than half the cost of operating the lamps. The alkaline battery has advantages along these lines which I believe will tend to decrease these items of cost so as to more than compensate for the higher cost of lamp renewals claimed by Mr. Swoboda—as to the magnitude or importance of the difference in lamp life I am not at the present time prepared to say.

It is claimed in the paper that a battery life of 2000 shifts is of no value because the life of other parts of the lamp is less than that. Inasmuch as the battery is a distinct unit separable from the rest of the apparatus, it is not clear why full use cannot be made of its longer life, the value of which is important because the cost of the battery is approximately half the cost of the entire outfit.

In regard to maintenance, we all know how carefully a lead battery must be handled in order that it may not be overcharged or overdischarged. The charging board recommended for use with the alkaline battery is so arranged that no meter need be used in connection with it, no rheostat need be adjusted and batteries are simply slipped under a pair of spring contacts and

left there as long as desired. It makes no difference if it be left there longer than is necessary or for a shorter time than is required, so far as the life of the battery is concerned. Upon a battery being withdrawn from the board, a resistance is automatically substituted for the lamp, which is designed to maintain constant the current flowing through the circuit, so that a battery can be slipped beneath the spring contacts or withdrawn without any further attention to the board being required.

I have here a battery in its metal container which is designed to be strapped at the miner's waist in the ordinary manner. The cover of the container is secured by means of a hasp and locked with a padlock or, if desired, by means of a magnetic lock. The cord from the lamp is connected with the battery by means of a special plug which fits into a corresponding socket on the cover of the lamp container. When the plug is inserted it is automatically locked by means of a spring catch and it cannot be again removed until the cover is unlocked and opened and the catch released from beneath. The lamp remains lighted, of course, as long as it is in the miner's possession.

The safety devices are similar in effect to those which have been already described. The battery, to be sure, is made up of two cells, but inasmuch as there are only two cells and the containers are metal, the two adjoining poles that are connected together to throw the cells in series are grounded upon the cans and the cans are positively connected with one another, so that no insulation is required either between the cells or between the cells and the container. The battery, therefore, acts as a single unit and may be treated as such.

The cells are rendered unspillable by means of the special valve construction. The valve stem extends to the center of the cell, at which point it is open for the emission of gases. The normal level of electrolyte is below the center of the cell, and therefore, in no matter what position the cell is held, the end of the valve stem is never submerged.

The electric lamp is a boon to the miner and is likewise desirable from the standpoint of the mine operator. It is inevitable that its use will in time become universal. It is, therefore, our plain duty to ourselves and to all others concerned to work together for this end.

R. C. Burrows: In regard to the comparatively high voltage and slow drop in voltage during discharge of lead cells, I would like to call attention to the lead cell using a paste electrolyte. This type of cell does not have the slow voltage drop during discharge that is characteristic of the lead cell using a liquid electrolyte. This is due to the increased internal resistance of the cell with discharge. In the cell with which I have had experience, this increase in internal resistance is not very objectionable: in fact, the discharge characteristic curve lies about half way between that of the lead cell with a liquid electrolyte and the alkaline

cell. There is on the market at the present time a very cheap lead cell outfit using sawdust saturated with sulphuric acid as an electrolyte. This little battery, as far as I have gone with it, shows up very favorably as to discharge characteristics and, with its low renewal cost, should meet a demand where breakage is high.

As to advantages of the alkaline cell as outlined, the necessity of using two cells in series is not serious from the standpoint of increased weight and the life of the incandescent lamps might possibly be increased by discharging the battery through rheostats until the voltage reaches a fairly constant value.

Regarding the figure of 1000 hours life for incandescent lamps, it is a fact that a lamp may be made to live a thousand years, a thousand hours, or one hour, all depending upon the efficiency at which it is burned. The present tungsten lamps would live indefinitely if they were burned at an efficiency equal to the best operating efficiency obtainable for the old carbon lamp. The life of incandescent lamps, then, is dependent on the efficiency at which they are burned and the most economical efficiency must be determined from a consideration of all the factors involved, such as fixed charges, interest, depreciation, renewal of lamps, cost of energy, etc. In fact in practically every case with a tungsten lamp, the greatest economy of light production is obtained when they average 600 or 700 hours instead of 1000 or more hours, as is at present the practise. In determining the length of life of incandescent lamps with these small outfits, we must consider the total cost of the light production and the effect of the lamp efficiency on the weight and cost of the battery. The total cost of light production is not given a great deal of consideration as a rule, but it is nevertheless of importance in this case. These small batteries are only about 50 per cent efficient, so that the effect of decrease in lamp efficiency on the output of the battery should be multiplied by two in determining the most economical efficiency. The fixed charges are high, due to the rapid depreciation of the cell, interest on investment of the outfit and housing, attention necessary, cleaning, etc. If the life of the incandescent lamp had been determined at 1000 hours, considering the cost of incandescent lamp renewals and energy alone, then, the life of the lamp should be somewhat less than 1000 hours, taking into consideration the fixed charges. If the ratio of fixed charges to the cost of the incandescent lamp were eight to one, the most economical life would be about 300 hours, instead of a thousand hours as stated by Mr. Swoboda. In fact, this figure of three hundred hours was adopted by the Bureau of Mines in their proposed specifications. The ratio of eight to one does not seem to be particularly high. For instance, with the cost of lamp as 35 cents, the fixed charges would be $2.80 per thousand hours burning, or for about one-third of a year.

To increase the life of the lamp from 200 hours to 1000 hours

means approximately 40 per cent increase in the ampere-hour capacity, or from 30 to 40 per cent increase in the battery weight and cost.

I might add that in a case I have in mind, the Ceag lamps for the same total lumens weigh nearly twice as much as an American outfit which uses a lamp of high efficiency with a life of three hundred hours.

H. O. Swoboda: Answering Mr. Clark's question regarding candle power measured, this refers to the lamps *with* reflectors. I received this statement from the manufacturers of the Ceag lamp.

Regarding the life of the incandescent lamps, the same manufacturers make the claim of having had lamps burn one thousand hours. The same statement is also made by Mine Assessor Schorrig of the Prussian Government, in one of the papers which he delivered in Germany last year.

Regarding the alkaline battery, mentioned by Mr. Smith, I found that two cells are undesirable on account of the complicated connections. A single cell is much simpler in this respect. The alkaline battery is also more expensive, as far as first investment is concerned. This point has to be considered very much, because the lamps in actual service are destroyed very rapidly and have to be replaced very often. For instance, if the first investment should be doubled by using alkaline batteries, it would mean that the depreciation charges would have to be increased also one hundred per cent and that will counteract, to some extent, the advantages which are claimed from charging without instruments.

Regarding the electrolyte used in the lead battery not being a liquid, I wish to state that the electrolyte of this battery (Ceag) is a liquid. It is common dilute sulphuric acid, such as is used in any storage battery.

Presented at the 293d Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 10, 1914, under the auspices of the Committee on Use of Electricity in Mines.

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THE DEVELOPMENT OF THE ELECTRIC MINE LOCOMOTIVE

BY G. M. EATON

ABSTRACT OF PAPER

The paper traces, largely by means of pictures, the course that has been followed in developing the mine locomotive to its present condition. The paper is limited to locomotives for operation in coal mines. The two main factors which have directed the development are, first, the demand for increased entry capacity, and second, the exploitation of thin seams. The early machines were high, and of irregular outline, whereas later machines are compact and strong, yet accessible, and easily inspected and overhauled. Various types of framing are illustrated. Locomotives with two and three axles in rigid wheel base, and also tandem locomotives, are shown and described. Reference is made to various methods of connecting the motors by which the adhesive weight is used to full advantage. Gathering locomotives, with vertical and horizontal reels, both axle-driven and with independent electric drive, are illustrated, and some of the problems of gathering work are briefly discussed. There is also brief reference to various types of motors with different methods of lubrication, as well as some reference to sleeve vs. frictionless bearings. The paper closes with a few tendency curves, and attention is called to the lines of future development which these curves apparently indicate.

THE evolution of mine haulage has been directed at every stage by the demand for increased capacity. This clamor for more tons at the tipple is successively relegating to the discard, both man and animal haulage.

Available headroom plays a close second to output requirements in molding the development of the locomotive for coal mines. Wherever the seam is too thin to permit free passage for the mule, the electric locomotive is the logical solution, and as thicker seams are worked out the field must become more and more monopolized by this type of motive power.

The thin seam, however, is not the only logical field for mine electrification. In fact, the earliest applications of mine locomotives were made for service in thick seams, where the chief aim was increased tunnel capacity.

Fig. 1 shows the first locomotive supplied for mine service in

1896 by one of the large builders of this class of machine. It weighed 43,550 lb. (19,754 kg.) and was equipped with two 75-h.p. motors driving through double reduction gearing and side rods. The block displacement of this machine, *i.e.*, length × height × width = 582.5 cu. ft. (16.5 cu. m.). Block displacement divided by h.p. = 3.88 cu. ft. (0.114 cu. m.) per h.p. A modern machine equipped with the same capacity of motors would have only 231 cu. ft. (6.48 cu. m.) block displacement or 1.54 cu. ft. (0.043 cu. m.) per h.p.

This is a measure of the increased demand for space economy in mine locomotives. This particular machine, shown in Fig. 1, was scrapped April, 1913, after 17 years of service.

Fig. 2 shows a locomotive produced in 1913 and is presented to emphasize the radical improvement over Fig. 1. A few of the main features wherein this improvement lies, are listed below:

1. Electrical equipment designed for mine service.
2. Staunchness of general construction.
3. Maximum protection of apparatus, without sacrifice of easy inspection.
4. Single reduction gearing.
5. Low height.
6. Short overhang.
7. Compact design.

All these features may be summed up as those contributing to produce a machine that will do its work reliably with a minimum of out-of-service periods.

Very few locomotives of the scraggly outline shown in Fig. 1 were put out for coal mining service. It became evident at an early stage of the development that a mine locomotive must be capable of withstanding severe collisions, and must sustain a minimum of damage from falling roof and similar emergencies. The locomotive design, therefore, soon settled down to an iron-clad machine with motors under cover, and virtually under an inverted box. This was for many years considered the ideal and only way to build mine locomotives, and is still thus regarded by some today. Cast iron was the almost universal material employed in the locomotive framing.

Fig. 3 and 4 show typical machines of the period, the first with frames inside the wheels, and the second with frames outside the wheels. Thus far the locomotive was used for nothing but main haulage, animal haulage being practically universal for gathering. This was a rather long-lived stage in the develop-

FIG. 1 [EATON]

FIG. 2 [EATON]

FIG 3 [EATON]

FIG. 4 [EATON]

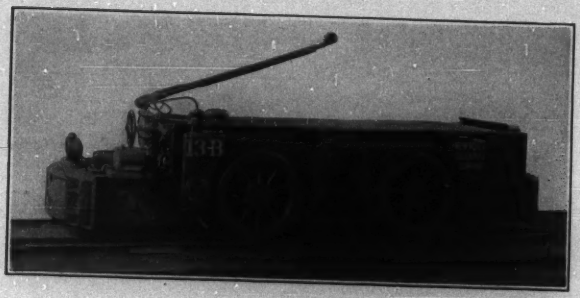


FIG. 5 [EATON]

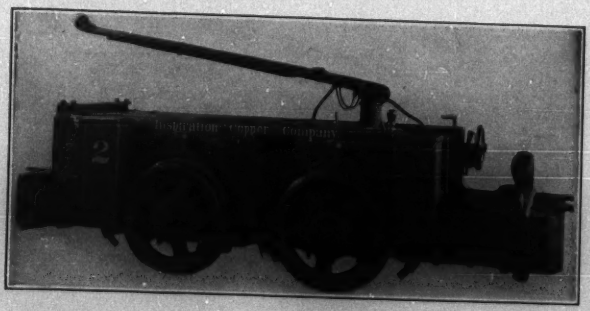


FIG. 6 [EATON]

FIG. 7 [EATON]

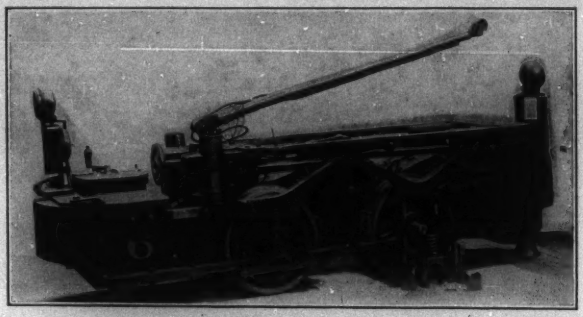


FIG. 8 [EATON]

FIG. 9 [EATON]

FIG. 10 [EATON]

FIG. 11 [EATON]

FIG. 12 [EATON]

ment of locomotive framing. The causes for gradual changing of ideas were fundamentally two. First, the entry of locomotives into gathering service, and the consequent necessity for lighter locomotives to negotiate flimsy, rough track in rooms, and second, the demand for greater strength to withstand the rough and tumble gathering service, and increasingly severe main haulage service.

Sections were trimmed smaller and more care was taken to put the metal where it would do the most good. It was the nrealized that it would be an excellent plan to produce locomotives which; if damaged in a wreck, could be repaired in the mine blacksmith's shop. Fig. 5 shows a locomotive with plate and angle framing, which meets this requirement to quite a degree. Such a machine is far lighter for a given strength than a cast iron frame machine., There is, however, a rather definite maximum weight limit beyond which it proved to be poor economy to push this type of machine. Larger machines when laid out with plate and angle construction proved to have such high weight economy that it was necessary to ballast them to give the weight required for adhesion, and when laid out with cast iron members the strength was sufficient for all ordinary requirements.

A step further with this general type of construction is shown in Fig. 6, where bent flanges replace the angles shown in Fig. 5.

In case of a collision with these plate steel frame locomotives, a certain amount of bending and buckling may occur, but the framing can be straightened up in the blacksmith's shop, and the locomotive returned to service with a minimum of delay.

Another type of frame which is extremely substantial and which lends itself to heavier locomotives consists of a single heavy rolled steel plate cut out to the desired shape. This type of frame is practically unbreakable, and it has been used quite extensively.

A very interesting combination of cast iron and structural steel frame is shown in Fig. 7. Several such locomotives have been turned out and have given good service. In case of a bad crumpling of the frame, the operator can secure a commercial angle and bar or he can carry a length of each in stock and can make quick repairs on the ground.

If the end casting breaks he can secure a new one and make replacement himself without an extensive disassembly of his machine. He can also lengthen the locomotive wheel base, should he so desire.

The next step was the cast steel bar frame shown in Fig. 2. This frame has been thoroughly demonstrated in steam locomotives and in electric locomotives for main trunk line railways. Its main advantages have been summarized under Fig. 2. Figs. 8, 9, 10, and 11 show the convenience with which such fundamental parts as brake shoes, armature bearings, oil wells, commutators, etc., can be inspected and maintained. The motor is open to air circulation and will therefore perform a given all-day service with less temperature rise than when operating in a more nearly enclosed space. For purposes of quick production the cast steel bar frame was at first considered inadaptable. If a large, special steel casting must be made for each new locomotive, quick production is difficult. Fig. 12 shows a locomotive with cast steel bar frame in which two pedestal openings at the left-hand end are cast in embryo, as it were. By machining out the lower chord of the frame in the wake of the proper pedestal opening, the same casting can be used for either inside or tandem-hung motors. This casting is also designed to suit either inside or outside frames. These castings can then be carried in stock in the more popular sizes of locomotive and comparatively quick shipments are possible. This type of frame lends itself to a certain amount of repair at the mine. It is, however, based more particularly on the principle of making a frame that will resist damage to a greater degree than plate and angle construction, at some sacrifice of the ease of making permanent local repairs. A bent frame can be heated and straightened at the mine forge. The chance of a frame breaking is very remote, in fact, out of the large number of locomotives with this type of frame produced to date by one large concern, only one case of cracked frame has been reported. This occurred in a severe collision, and the frame was replaced.

In steam locomotive practise, the great length of the cast steel frames, and the heavy strains incidental to high speed and high power, cause considerable frame breakage. Welding by either the thermit or the electric process proves very satisfactory, and could be employed in the event of breakage in mine service. The thermit process would be the most practical, especially in small operations, on account of the simplicity of the necessary equipment.

To meet the demand for the maximum drawbar pull with a minimum of weight, a variety of types of locomotives has been introduced. The first locomotive illustrated in Fig. 1 shows one

effective method, namely, the coupling of the axles by means of side rods. In this machine, rod drive was adopted as a ready means of applying standard industrial motors rather than for the purpose of securing maximum drawbar pull.

Fig. 13 shows a locomotive equipped with a single motor geared to one axle and rod connected to the other, to secure the total weight for adhesion. In this type of machine, the advantage of simplicity and smaller number of parts is secured with the sacrifice of the advantage of the series parallel connection.

The same general result is secured by connecting the axles of a single-motor locomotive by one or by two chain and sprocket systems, instead of by side rods.

Another method consists of gearing a single motor directly to both axles. The motor may have its shaft parallel with the axles with double reduction spur gearing, as shown in diagram

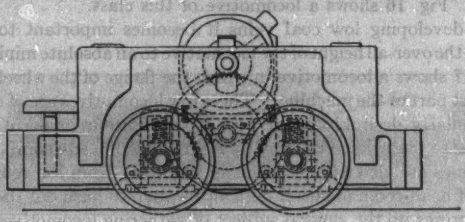


FIG. 14

in Fig. 14, or the motor shaft may be longitudinal, with bevel gearing.

In all of these arrangements, the reduced complication of the single motor is more or less offset by the great complexity of the transmission system.

In the early locomotives, cast iron wheels with chilled treads were universal. The introduction of steel-tired wheels was first made to secure a longer wheel life. These wheels, however, also contributed the advantage of greater adhesion, particularly with sand. The ultimate possibility in drawbar pull with a given weight of locomotive is of course the rack rail machine.

In the pursuit of greater capacity on a given gage, or to suit a fixed cross-section of entry, the next logical step after maximum drawbar pull is secured from two axles, is, in mine service, as in trunk line locomotives, the addition of more axles. The history of the mine locomotive, however, is different from the trunk

line machine in that the first step which was broadly applied in the mine locomotive was from two axles to four axles and later, in a few cases, to three axles. This of course was due to the almost universal existence of sharp curves that strictly limited the available wheel base. Fig. 15 shows a tandem locomotive. This particular machine is not necessarily permanently coupled. It is equipped with a single controller on the left-hand half, which handles all four motors. Flexibility of operation is secured by equipping the right-hand half with a controller capable of handling two motors only.

The locomotives can thus be operated as single or double units according to the exigencies of the service. Also, in case of injury to one half, a minimum of reduction of mine output occurs.

When the main entry is laid out with liberal curves, it is possible to have three axles arranged in a single long rigid wheel base. Fig. 16 shows a locomotive of this class.

In developing low coal veins it becomes important to keep down the over-all height of the locomotive to an absolute minimum. Fig. 17 shows a locomotive in which the flange of the wheel is the highest part of the machine. These low locomotives are of course particularly desirable where bad roof conditions make it inadvisable to blast down the roof to secure added head-room. Such machines are also advantageous in gathering from low rooms, as lack of head-room makes it difficult for men to push out the cars. This brings up the general subject of gathering locomotives.

At first the gathering locomotive was simply a small edition of the main haulage machine. Such a locomotive of course requires in the rooms steel rails more or less effectually bonded, and a trolley wire.

For various reasons it is often undesirable to introduce these features into the rooms. The cause may be danger to the miners, gaseous condition of the mine, or expense. These objectionable features are partially overcome by equipping the locomotive with a reel carrying a single-conductor cable, as shown in Fig. 18, and running steel rails, but no trolley wire into the rooms. A still further elimination is secured by fitting the reel with a double-conductor cable, when unbonded steel rails, or wooden rails, can be employed. With wooden rails, the locomotive weight is practically limited to about five tons.

Another method of eliminating the undesirable features is the application of the storage battery to the gathering locomotive. This is a comparatively recent development, but with the modern storage battery with its ability to resist mechanical shocks, the

FIG. 13 [EATON]

FIG. 15 [EATON]

FIG. 16 [EATON]

FIG. 17 [EATON]

FIG. 18 [EATON]

FIG. 19 [EATON]

FIG. 20 [EATON]

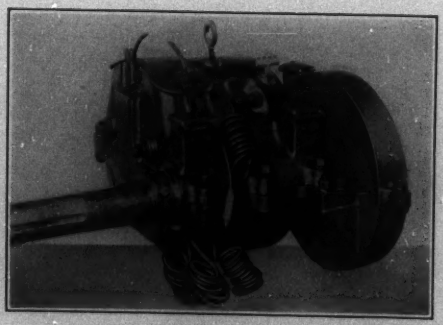
FIG 21 [EATON]

FIG. 22 [EATON]

FIG. 23 [EATON]

[EATON]

FIG. 24

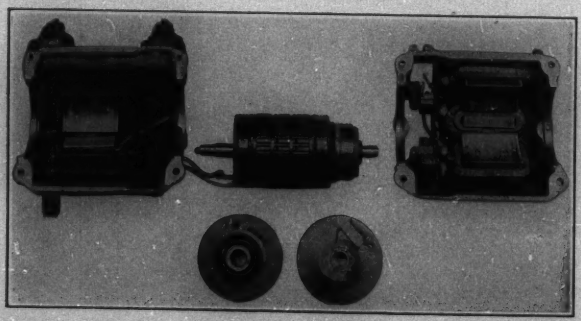


[EATON]

FIG. 25

[EATON]

FIG. 26



[EATON]

FIG. 27

locomotives of this class have given promise of being thoroughly practical.

The locomotive can gather from the rooms without entering them if a traction reel or crab is installed on the locomotive, as shown in Fig. 19. This type of locomotive can haul cars from the rooms, but of course cannot deliver empties to the face.

A comparatively small number of locomotives have been produced on which both types of reel are applied.

The earliest form of cable reel was driven from one axle by a chain. Two general types are in use, one with its axis vertical, as shown in Fig. 20, and the other with its axis horizontal as in Fig. 18. Both have an inherent weakness. When the rooms dip to the entry, it is necessary to brake the locomotive when bringing the car out. If the wheels from which the reel is driven slip on the rail, the cable slackens, and is liable to be run over and cut in two. To overcome this, two types of reel have been produced, one with long clock springs, which are wound up on entering and which unwind and recover the cable on the return. A later general type is driven by an independent motor which is connected across the line through a resistance and is in effect an electrical spring.

There are here as in the case of the axle-driven reel the vertical axis type and the horizontal axis type as in Fig. 21. In the latter type the armature is inside the reel. Fig. 22 shows the method of removing an armature. The resistance used with this type of reel is the heater type of resistance where the resisting element is mica-insulated and hermetically sealed in a steel tube.

A traction reel with bevel gear drive is shown in Fig. 23 in rather more detail than in Fig. 19. The reel can haul through an angle of slightly over 180 deg., or over 90 deg. from the track on either side.

As locomotive development has been perfected, attention has focussed more and more on facility in overhauling. For example, in the early types of locomotive with frames outside of the wheels, it was necessary in order to remove a journal box, to drop the axle or jack the locomotive till the box was entirely clear of the side frames. Fig. 4 showed a locomotive where this is necessary. Various designs were later adopted where this is avoided. Fig. 8 shows another solution where the pedestal gibbs are interrupted and when the locomotive is jacked sufficiently to slack the spring the segmental pedestals are out of mesh and the box will slide out freely. This feature is representative of many details that have been similarly improved.

As has been previously stated, the earliest locomotives were electrically equipped with apparatus designed for other types of service. As the electrification of mines gained headway, it became evident that the severity of the service demanded more sturdy equipment. The motors received the first attention. Some of the leading types will be reviewed. The motor used on the locomotive shown in Fig. 1 was a bipolar type and is shown in Fig. 24. Fig. 25 shows a motor split through the axle. A very large number of locomotives are running with motors of this class. The overhauling of such motors and particularly the renewal of axle bearings is more difficult than with many of the later designs. This motor in common with all the earlier types is arranged for grease-lubrication of both axle and armature bearings. Such bearings in general require the addition of lubricant at least once a day, and sometimes much oftener. With proper attention, however, they have given very good results.

Fig. 26 shows a motor with independent axle caps. Both axle caps and suspension attach entirely to the lower half of the frame. This permits of ready overhauling of the motor. The excellence of this general arrangement was first proved in city and interurban railway service and it proved equally successful in mine service and has been widely adopted.

The great advantage of oil and waste lubrication over the earlier grease lubrication was proved in the street railway motor. Its wide success in this field led to its introduction into mine service. Fig. 27 shows a mine motor so equipped.

This experiment was entirely successful and was also widely adopted. This form of lubrication in combination with high-grade bronze bearings is in fact so thoroughly successful that it is still considered by some locomotive builders to be the best all-around solution. In one complete line of motors that has been on the market for some years, there has been no case reported where this type of bearing has failed. Other builders in discarding grease bearings have standardized on various well-known types of ball or roller bearings. It is to be hoped that the comparative merits of the two general types of sleeve versus frictionless bearings will be brought out in the discussion.

In addition to the mechanical improvements of the motor, the electrical designs have made a great advance. The most notable feature has been the addition of commutating poles. This is of particular advantage in mine service, where there is little or no coasting, so that there is no chance to polish the com-

mutator. In such service, the best of commutation is essential. Fig. 27 shows a typical arrangement of motors with commutating poles.

The motors of today are designed with particular reference to securing a high continuous rating, since this means the greatest tonnage delivered at the tipple.

In the early days the resistance gave a great deal of trouble. Various forms of cell and ribbon type resistance were employed. These were gradually superseded by grid resistance, till today this is the accepted standard. The first introduction of grid resistance, however, was by no means the solution, and both

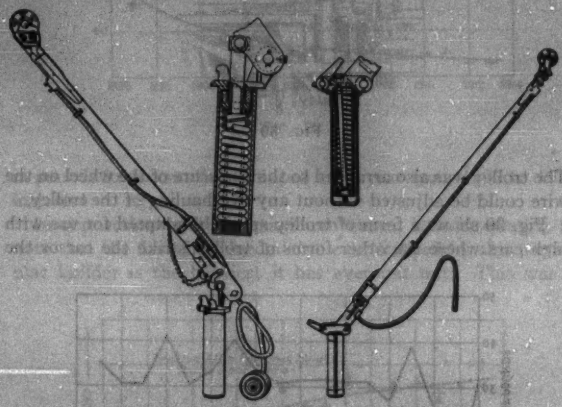


FIG. 28 FIG. 29

manufacturers and operators could fill an evening with harrowing reminiscences of grid resistance grief.

The first controllers applied to mine locomotives were series-parallel or type K controllers. The size and particularly the height of this type caused the early adoption of the rheostatic or type R controllers. The early R controllers were without means for series-paralleling the motors. The reverse drum was later modified to include a series-parallel switch. The next improvement was the incorporation of means to make it more difficult to buck the motors. Magnetic blowouts have been used on all these controllers.

Fig. 28 shows an early form of trolley which was widely used. This was later superseded by the trolley shown in Fig. 29. The

principal changes which were made in this latter trolley were for smoothing out the contact pressure curve; that is, a proportioning of the operating mechanism details, so that within the working range the pressure on the trolley wire would remain approximately constant, regardless of the height of the trolley.

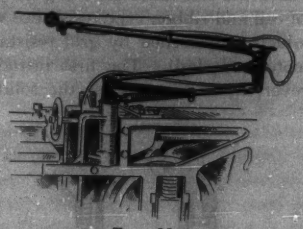


FIG. 30

The trolley was also arranged so that pressure of the wheel on the wire could be adjusted without any overhauling of the trolley.

Fig. 30 shows a form of trolley specially adapted for use with high cars where the other forms of trolley strike the car or the

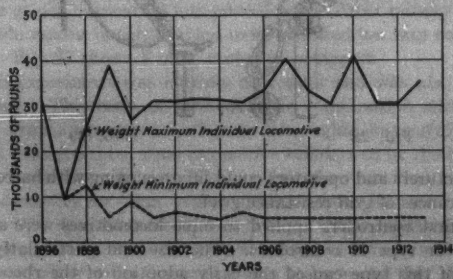


FIG. 31

coal in the car. This trolley is also adapted for use in the iron mines.

Many other detail developments could be pointed out, but it seems preferable for these to be brought out in the discussion.

The following curves show roughly the trend of the times in a few lines of development. These curves are based entirely upon

the locomotives built by one manufacturer, but it is believed that they are fairly representative.

The curves in Fig. 31 show the maximum and minimum weight

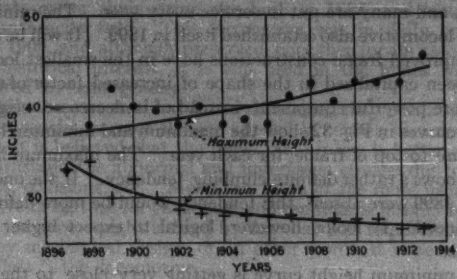


FIG. 32

in pounds for locomotives shipped each year from 1896 to 1913 inclusive.

In connection with the maximum curve, it is interesting to note that the first mine locomotive ever shipped by this particular builder is the heaviest it has ever put out. This was a

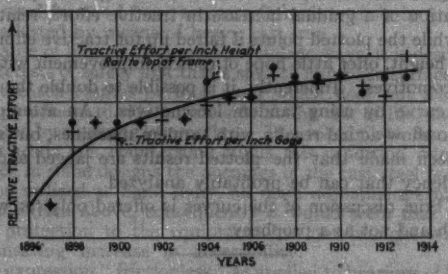


FIG. 33

three-axle machine, and is therefore not included in this curve. There is no pronounced tendency of the maximum curve. In 1899 a two-axle locomotive was built, weighing approximately 40,000 lb., (18,143.7 kg.) and several of about the same weight have been built since that time. This limit has held for so long

in coal mine service for this type of locomotive, that it seems to be pretty definitely settled.

The minimum weight locomotive has had less sharp variations. This is natural because far more locomotives of this size are required, and many are put in service every year. The minimum weight locomotive also established itself in 1899. It will be noted that improved frame constructions have in the smallest locomotives been capitalized in the shape of increased factor of safety and more powerful equipment instead of in decreased weight.

The curves in Fig. 32 show the maximum and minimum height from rail to top of frame, for each year. The maximum height curve shows a rather definite climbing tendency. If the one high spot in 1899 were absent, this tendency would be more definitely pronounced. It looks, however, logical to expect higher locomotives.

The minimum height curve is getting very close to the horizontal. It seems probable that no radical decrease is to be expected, as there is great inherent difficulty in operating these exceedingly low machines.

The curve in Fig. 33 shows in a striking manner how power has been crowded into a continually smaller space. The term power is used advisedly although the curve is based upon tractive effort, because the speeds involved in the years vary very little.

The general tendency of this curve would seem to justify the expectation of a gradual increase in tractive effort, relative to gage, while the plotted points if faired up for tractive effort relative to height, offer little hope of radical improvement with two-axle locomotives. Inherently, it is possible to double the height of the curve by using tandem locomotives. An attempt was made to show actual results with tandem machines, but so few have been made that the plotted results are jagged and show no tendency that can be profitably analyzed.

This brief discussion of the curves is offered only for what it is worth and not as a prophecy.

DISCUSSION ON "THE DEVELOPMENT OF THE ELECTRIC MINE LOCOMOTIVE" (EATON), PITTSBURGH, PA., APRIL 10, 1914.

W. W. Miller: Referring to Mr. Eaton's paper, it may be of interest to note that a mine locomotive of 14,000 lb. weight with a single motor chain drive was built in 1886, and installed in the anthracite field. This locomotive was in daily operation until 1909, and although preserved since then for its associations and historical interest, it is still used in the mines whenever required by emergencies.

While the cast steel bar frame mentioned may permit a design of less weight to meet stresses applied in certain assumed directions, it is believed that the rolled plate frame is better adapted to withstand the abnormal and unforeseen stresses due to derailments, collisions, etc. Moreover, in all of the more usual sizes, *i.e.*, five to six tons for gathering, and ten tons or heavier for main entry service, weight is fixed by drawbar pull requirements and not by mechanical design, or, in other words, it is necessary to "ballast" the locomotive.

With the rolled plate frame, this ballasting is accomplished by increasing the power section, thereby maintaining the weight distribution over the axles and making the locomotive power so much the stronger and more stable. Ballasting by means of heavy cast iron bumpers, as is sometimes resorted to with the cast steel bar frame, has the disadvantage of causing unnecessary power stresses and giving a strong tendency to tilt, unless the wheel base is of more than the usual length. Also the integrity of metal in the rolled plate frame is believed to be superior to the best of castings. It might be well to state that some of the rolled steel frames I have seen are from five to six inches thick, and ballasted by means of heavy cast iron.

Because of limited clearances in haulage ways, it is desirable in the interests of safety first that a smooth unbroken surface, which cannot catch clothes or tools, and which does not allow trip riders or miners to ride on the side at the risk of life, should be presented by a passing locomotive. The rolled plate frame with all bolt heads, etc., countersunk fulfils this condition admirably.

While in some designs the openings of the cast steel bar frame may be utilized as hand holes, all main adjustments must still be made from above, consequently it would seem that the lessened protection to the equipment has not brought with it a compensating increase in accessibility.

The expression "frictionless" as applied to bearings of the ball type in contradistinction to the usual sleeve type, does not emphasize their most important characteristic. While experimental tests seem to indicate considerably better starting torque due to their use, and it would seem reasonable that their lower friction coefficient would save something in full speed operation, their most important quality is in maintaining the absolute integrity of the motor air gap.

Few people realize what a large proportion of armature and commutator troubles have their inception in bearing wear. With ball bearings in a properly designed housing, so that they are dust protected, and with even fair attention to lubrication, the wear is entirely negligible. Recent inspection of such bearings after 20,000 miles of locomotive operation, showed wear that could be measured only in the ten-thousandths of an inch.

C. W. Beers: I am very much interested in Mr. Eaton's paper on electric mine locomotives, and as they are important factors in the production of coal, I would like to refer to some of the features which I consider to be essential to good locomotives.

As to the locomotive cover, it was originally made of wood, resting snugly on offsets in the side frames. In time these wooden covers would swell and cause trouble. A scheme that I have adopted with apparent benefit is similar to the cover shown in Fig. 2 of Mr. Eaton's paper, except that each cover piece extends over the side frames about two inches on each side. The cover plates are so supported on circular supports that they are about one and one-half inches above the side covers. This is a very good plan, as it gives free vent to the heat that is generated and permits the locomotive to cool more quickly.

I have found that the ordinary cover on the main journal bearings is not a satisfactory device for keeping out the grit, sand, etc., from the brasses, as in time this lid will not close properly, and hence the wash and sand from the locomotive will find an entrance. This causes a rapid wear of the brasses, and a tapering wear on the axle. To overcome this, I have adopted the plan of having this cover lid arranged to bolt fast to the bearing, and so far, I have found it to work out satisfactorily.

The old method of running the cables from the controller to the rheostat and motor was very unsatisfactory, as the cables would bunch on top of the motor and the vibration would damage the insulation. To overcome this feature, I have arranged on our later locomotives that cables coming from the controller should be placed in a built-up metal box, fastened to the inside top edge of the locomotive side frame, and from this main cable box the various cables would run straight out to the motor and rheostat. This makes a very satisfactory job, and keeps the top of the motors clear, as well as reducing cable troubles.

The old method of attaching cables to the rheostat by means of set screws was responsible for much trouble, as the screws would work loose or cut the cable and cause damage. We have overcome this trouble in our later type by using a clamping connection.

The brake reach rods in some of the locomotives pass over the top of one of the motors. This caused much annoyance when repairs were in order, as it meant dismantling part of the brake rigging. By having the reach rods pass along the side of the motor, this annoyance has been eliminated.

The arrangement of the foot pan is usually bad, because it

is usually bolted to the bottom of the side frame. This is shown in Figs. 8, 9, 10, 11 and 12 of Mr. Eaton's paper. Hence, when the locomotive rides over an obstruction, these bolts are liable to be torn out and the foot pan drops and may break the operator's legs. By fastening this foot pan to the iron ledges attached to the inside of the side frame, this danger is removed.

The ordinary covered and braided cables that are used for connecting the various parts of the locomotive to the equipment are not usually very successful, as the braiding soon separates and becomes fuzzy and in damp mines this is rather annoying. I think that cambric cables, with a hard, wear-resisting braid of good quality, could be used to advantage.

In regard to circuit breakers, I prefer a circuit breaker if it is a good one. I do not believe, however, that the development of the locomotive circuit breaker has kept pace with the other parts of the equipment, and the circuit breakers furnished today on some makes of locomotives are very poor devices. The breaker should be stout to resist bumps, etc., it should be waterproof, and so arranged that it cannot be kept from operating by the use of the foot, sticks, wires, etc.

The development of the mine locomotive is a problem that cannot be put up entirely to the designing engineer. Rather should the experiment be brought about by the operating man, and by careful watching, many defects can be remedied, as I have found that the desiging engineer is usually very glad to co-operate with the operator. Many of these points which I have mentioned are the result of my observation and of conferences with these men.

The maintenance of the mine locomotive is largely a question of looking after details. Generally, the manufacturing companies handle the question in a very satisfactory manner, but it is usually the little things that happen in every-day operation that they are somewhat unprepared for, and it is here that the operating man could be of use.

For some years past I have endeavored to keep a record of locomotive costs, the costs to cover armature repairs, field coils, armature bearings, journal brasses, wheels, axles, gears and pinions, also brake shoes, controllers, rheostats, trolley poles, oil, grease, crabs, reels, sand, brushes, journal springs, etc. By getting these various costs for each coiliery, curves can be plotted that will give a graphic comparison of the costs for each place, and by means of personal knowledge of the conditions at each place, due to long experience, it is usually an easy matter to take any colliery and point out the proximate reasons and causes for the high costs.

For instance, high rheostat costs, combined with high journal spring costs, indicate bad tracks, cross-overs, etc., and high brush costs and high bearing cost usually mean high armature costs; or, again, high wheel costs usually follow the sand curve, etc.

A close study of such a set of curves will indicate very closely what part of the locomotive needs redesigning to better advantage, or what internal conditions need attention.

From curves plotted in this manner, it would seem that the costs of armatures, bearings and brushes were closely allied. An investigation showed that bad armatures were usually caused by bad bearings. Naturally, if the bearings were bad the armature would not run true, and this caused commutator troubles which put the finishing touches to the armatures.

During the past year I have had thirty-nine armatures sent to the repair shop with old bearings attached, and instructions were forwarded to the repair department that as soon as an armature was received, its shaft should be trued up and the bearings babbitted to suit. Out of thirty-nine armatures thus sent out, only one was sent back for repairs. This appears to me to be investigation in the right direction, and also points out the fact that armature bearings can be further improved.

The brushes also came in for their share of experiment, and we find that massive pigtails are a distinct advantage. The pigtails ordinarily furnished are not particularly good. The pigtail should be so large that it shunts practically all the current from the brush holder to terminal, and thus relieves the brush holder of its electrical function as a conductor.

We are now conducting experiments with impregnated field coils, but up to the present time have nothing definite to report.

Referring again to locomotive costs, it may interest some to know the relative percentage of these costs. My experience indicates the following:

Armatures and bearings	16.60 per cent
Field coils	3.10 " "
Rear axle bearings	1.43 " "
Journal brasses	1.12 " "
Wheels and axles	14.90 " "
Pinions	0.75 " "
Gears	1.73 " "
Brake shoes	1.15 " "
Controllers	2.10 " "
Rheostats	1.24 " "
Trolley repairs	3.35 " "
Oil	1.29 " "
Grease	0.51 " "
Sand	6.13 " "
Brushes	0.72 " "
Journal springs	0.50 " "
Reels and crabs	3.00 " "
Miscellaneous material	16.46 " "
Labor	23.80 " "

It should be noted that this cost also includes warehouse material that has been purchased and charged out, although no use has been made of it up to the present time.

Probably the most frequent cause of locomotive trouble is due to bad bearings. When buying a new locomotive, we find that it will run from eight to fourteen months without much repair, after which time it is usually necessary to replace the wheels, and from this time on the repair costs are usually high.

In an endeavor to find out the cause of such increase, I have reasoned the matter out in this way: When new, the bearings and all parts have a good clean fit. After a time the use of sand is introduced, and this simply accelerates the wear, and soon the bearings are no longer good and considerable play is in evidence. Just about this time the gear and pinion show considerable wear, and begin to pound. This has a very bad effect on the armature and produces a bad effect on the commutation, and the armature is no longer central. Consequently the brushes get hot, the commutator blackens and the armature is then in line for repairs. After watching this performance a good many times, I have come to the conclusion that, since it is impossible to stop the use of sand, some form of bearing, both for rear axle and main journal, should be designed that is sand-proof. The armature bearings, of course, should be sand-proof, and in addition should be hard enough to stand the pounding of the gears, and both the sleeve type and ball bearing type appear to be improvements in the right direction.

During the past, our experience with gear wheels indicated that there was much to be desired concerning them, and from data that we have I find that gear costs follow closely the wheel and axle costs, and to my mind that indicates quick wear of gears and pinions and hence rapid wear of armature bearings due to the pounding of the gears. We are now trying out some extra hard gears and pinions, and expect to get better results.

Probably one reason for excessive gear and pinion wear is due to the fact that gear cases are not constructed to keep out dirt and grit. These find their way into the gear case grease and, of course, cause rapid wear. It occurs to me to ask if any one present has operated his locomotives without the lower half of the gear case.

In speaking of the reel or crab, Mr. Eaton says that locomotives equipped with this device cannot deliver empty cars to the face. This is not my experience, as I find in pitch regions that the crab can do this very well by means of a dead rope and a bull-wheel in the face, or by carrying the rope to the face. On the same page Mr. Eaton describes a clock spring reel. The idea is good, but it is very expensive to maintain, and I do not recommend its use.

Regarding the use of ball bearings, we have a few in use. They are good, and better than the babbitted shell. They are rather expensive to renew, but they do keep the armature in good shape. My experience has not extended over a sufficiently long period of time to state whether or not they are

better than the sleeve type, but almost any type is preferable to the babbitted shell, as these are usually soft and are easily pounded.

On account of the poor tracks which are encountered in the mine, it appears to me that grid resistance should be more flexible. A broken grid is usually responsible for ultimate armature and controller trouble.

Carl J. E. Waxbom: With reference to the design of electric mine locomotives, we believe that some stress should be placed upon the "safety first" idea, and we found it absolutely necessary to adopt a type of frame which was unbreakable, and such a type of frame is found in the rolled plate or slab frame construction. We found that the use of cast frames, whether of steel or iron, has always resulted in some flaws being found in the castings, and this experience, I believe, will be borne out by everybody. Therefore, I think that the rolled plate frame has overcome that objection.

With reference to ball bearings versus sleeve type bearings, I think that the ball bearings have a decided advantage, inasmuch as they lessen the cost of operation and upkeep of the locomotive, particularly that of the armature. This cost, I have found, in some cases amounts to as high as 80 per cent of the total cost of the upkeep. We applied some ball bearings some six years ago, and they are still running without any wear. I have also found users of mine locomotives who have expended, for a year's service of 16 locomotives, only $10 for the cost of lubrication. These locomotives, as I recollect, have been in service for over two years, and after a periodical examination of the ball bearings there was no perceptible wear on them.

The most important point in our opinion is that in the design of ball bearing housings care should be taken so as to preclude any foreign material getting into them, and with that design I would say that the ball bearing, with proper lubrication, should last indefinitely, or just as long as any other part of the locomotive.

With reference to the frame construction, I believe that the rolled plate type of frame should be recommended, even in case of the largest type of mine locomotives. I think that safety should be the first consideration in the design of mine locomotives, and I think that it is entirely met by the plate type frame construction, which, as one speaker stated, runs up to as high as six inches in thickness.

Graham Bright: I do not believe that the illustrations show nearly all of the advantages that are obtained in the open steel bar type of frame. The question has just been brought up in regard to the safety of this type of frame, in that men are liable to jump on the locomotive, and may slip and have their toes cut off. I have talked to several mine operators who are using this type of locomotive, in regard to this point, and they seem to think, while it might possibly occur in some mines, there are

probably only one or two openings where this could possibly happen, and they were willing if absolutely necessary to close those openings up with small plates and get the advantage of the other openings for inspection and ventilation.

There is no doubt in the case of the box type frame that, due to the heat losses of the motors and resistances, the temperature must get pretty high inside the box, there being practically no ventilation, and since the capacity of the locomotive depends on the continuous rating of the motors, (not the hourly rating,) for all day's service, there is no doubt that this continuous rating must be considerably increased by the ventilation obtained by the open steel bar frame.

Mr. Eaton states that with the single motor and side rod, you are not able to obtain a series-parallel combination of the motors. I mentioned yesterday in discussing Mr. Reed's paper that I thought this was more fancied than real, because in most cases you will find the motorman will not use the series combination on the controller. In the parallel position it gives a little easier start and he does not have to worry about changing the position of the reverse lever if he wants higher speed, and the result is that he seldom uses the series position. Unless we can obtain a series-parallel type, like a railway controller, that is low enough to be used for gathering service, I do not think there is much in the series-parallel combination, from a power economy standpoint.

Mr. Eaton calls the ball bearings "frictionless" bearings. Some tests have been made on a motor, with both ball bearings and with the sleeve type of bearings, in order to determine the difference. At very low speeds there is no question that the ball bearing has considerably less friction, but at m dium and high speeds the difference is scarcely noticeable. In fact, some tests show that more friction is obtained with the ball bearing than with the sleeve type of bearing. Unless a ball bearing is properly lubricated and protected from dust it will very quickly give trouble and when repairs are required they will prove very much more expensive than with the sleeve type.

When the first mine locomotives were brought out, the motors as a rule did not have sufficient capacity for the service to which they were put. The result was that the electrical repairs were very high. There seems to be lately a swinging toward the other direction, and many operators and some consulting engineers are insisting on capacities which are really far in excess of what is necessary to perform a given service. The result is that the electrical repairs go down, but, on the other hand, the mechanical repairs mount very rapidly. The reason why these mechanical repairs are not so evident is that when the electrical trouble takes place as a rule you have no warning until the trouble actually occurs, there being no indication of what is going to happen. In the case of mechanical repairs, they can always be foreseen far enough ahead to have

repairs made without delay to the service. The result is that these high mechanical repairs are really not made manifest, but I think you will find where a locomotive is very much "over-motored" that the low electrical repairs are brought about at the expense of high mechanical repairs.

F. L. Stone: There has been a great deal said about the increased ventilation and the beneficial effect of the open side locomotives as compared with the box frame. I would ask if any concrete tests have been made to substantiate the claim. Personally, I do not think it amounts to anything, because the box locomotive is open both top and bottom, and the fact that the sides are closed does not, I believe, make any material difference.

G. M. Eaton: While I have no definite comparative tests of mining locomotives with solid and bar frames in exact conditions of service, I would call attention to the fact that in testing a motor in the shop, if one inadvertently leaves the window open, perhaps ten feet away from the motor, on a day that is moderately cool, there is a very great difference in the results that are secured. Personally, I have no doubt that if the motor can run in free and open air, that is cool, it increases the capacity of the machine.

L. J. Ilsley: In regard to locomotives being "over-motored" or "under-motored," in my experience with several different types of locomotives, it seems that the average motorman is inclined to haul just about all the locomotive will haul; it is the same old question—if he had a mule that would pull three cars, he would attempt to pull four cars with it. If he could easily haul four cars with a locomotive, he would try to haul six cars. I have known of this problem being met by reducing the gear ratio, and by using heavier motors, so that the motorman can only haul a certain load, and, therefore, not overheat his armature and his field coils. This is harder on the wheels and the brake shoes, but I think, on the whole, it is a saving to the mine operator.

In regard to the cable reel which is operated by a motor, and reels out against the torque of the motor, I had experience with a different type of reel which works on the same principle, and this reel seems to work very well, except in cases where the trolley voltage is very poor. In the earlier types of locomotives there was a tendency in the controller design to make the terminal posts so small that one could get only a portion of the lead wires in them; one had to cut them down in assembling the wires. I am glad to see that in the later designs they have made ample room for putting in the leads both in the rheostats and in the controllers.

The question of the design of a mine locomotive should, in my opinion, receive special attention with regard to making repairs on the locomotive, for the average mine is not usually equipped with the best advantages and facilities for making

repairs. In the railroad shop you have your jacks and everything you require to handle the locomotive, but in the mine you may have a small pit out at some distant portion of the mine where you make your repairs, and, therefore, the locomotive should be designed to assist the repair man in every way, in changing armatures, wheels, and bearings. My experience in the maintenance of locomotives has shown that a great many of the troubles due to armature and field coil burn-outs are due to lack of inspection of the equipment.

W. W. Miller: I think the usual tests made on the motors Mr. Bright mentioned, with ball and sleeve bearings, are made with the same motor, with the same air gap. We have found, after considerable experiment, that you can use a much smaller air gap with a ball bearing motor. This means an increase in efficiency, with a resultant saving in kilowatts consumed. Recent tests on a considerable number of motors of various manufacturers indicated such material discrepancies in the service capacity of the motors having the same ordinary rating, that it would seem any slight advantage in external ventilation is entirely negligible, compared with the inherent electrical design and loss distribution of motors.

F. L. Stone: Mr. Eaton's reply to my question in regard to the actual heating tests on locomotives with open frames having been made, is only a partial answer. I agree with Mr. Eaton, that a motor would run cooler in a sealed room with one window open than it would with the window closed, but I question, if the motor was in a room with five windows and four of them open, whether the opening of the fifth window would make any material difference in the temperature rise of the motor.

W. A. Thomas: Some mention has been made as to the cost of production of various types of frames. Admittedly, a defective casting in the foundry does increase the cost of the cast steel frame. The structural shapes and plates we know, from market prices, can be purchased in a varying market from $1\frac{1}{2}$ to $1\frac{3}{4}$ cents per pound, and if any of you have had occasion to buy steel castings you found they cost quite a bit more per unit of weight.

Mr. Miller brought out an important point with reference to the use of ball bearings, that the easier starting is undoubtedly true with the ball bearing, because it is a point contact, and is, as Mr. Eaton brought out, somewhat frictionless. For that reason it is my judgment that there is a decided field for the ball bearing, especially in gathering work, which is made up of starting and stopping much of the time; but in the main haulage work, the use of ball bearings and that of the sleeve bearings has not had, relatively, enough trial to determine their respective merits, although one large operator, who tried locomotives of different design and of different manufacture, and all with the ball bearings, with the best design of housing obtainable, has stated that the advantages of the ball bearings which

they had hoped for, had not been obtained, and therefore in their later locomotives they were resorting to the oil-waste-packed sleeve bearing. That is only one case under one set of very severe conditions.

The contention that there is no wear in the ball bearing is theoretical. Experiments have shown that there is wear. Resorting to smaller air gaps to get more power out of a given weight has resulted in offsetting the main advantages of the ball bearing by the armature going down in the tail pieces on comparatively slight wear.

Another point which Mr. Beers brought out is an important one, with reference to the use of babbitted bearings, babbitt metal being subject to hammering from poor alignment of gears. This applies again because, as I think the last speaker brought out, you cannot get proper inspection of the equipment under various conditions of installation, and you get a very heavy hammering of the bearings due to the condition into which the gears wear. This, in some cases, is breaking the ball bearings and causing replacements, and in some cases the bearings will last only six months, being comparatively expensive to maintain.

It is extremely difficult, as Mr. Beers pointed out, to keep the sand out of any bearing. This is, perhaps, more important in the case of ball bearings than in the case of the sleeve bearing, because with the latter full of oil, the sand, if it gets into the bronze brushing, has a tendency to be carried out, whereas with the point contact there is a constant grinding, due to the fact that no attempt is made to keep a flow of oil through the bearings.

As regards the matter of safety, this appears to be largely theoretical, as is indicated by a recent order which the manufacturers have had for a bar type construction, in which order they have been requested to put in step plates in the end openings of the frame for the trip rider to get on.

The question of motor capacity should, perhaps be, qualified. Increased motor capacity obtained by speed has no advantage, because you have no greater tractive effort, relatively; and consequently—while the bare statement of power would appear advantageous—the speeds go beyond the practical limit, and the fact that you can only accelerate a certain train with a given tractive effort removes the advantage of the increased power. As a matter of fact, it is thought by some, and that thought has merit, that the question of the tractive effort in terms of the one-hour capacity of the motor, as laid down by the Standards Committee of the American Institute of Electrical Engineers, should be the prime consideration of the relation between the electrical capacity and the weight of mechanical equipment.

It is interesting to note in connection with the discussion of the gathering proposition, that as far as we are able to determine, and from my personal observation, the storage battery was the first type of gathering locomotive tried out. That

represented, of course, a battery of fifteen years ago, which was tried out at the Pocahontas Collieries at that time, and the electrician, after burning out several suits of clothes with acid, devised what was known as the "Wampus." The motors were hung outside in order to put the battery in the center. That left a relative short wheel base, with a clear field underneath the battery, so that when the battery was removed he took an old electrical wire reel, with wooden flanges on it, and put a shaft through it, and wound his cable up on this old reel. Then he mounted on the end of this shaft a large wooden disk, and on that end of the shaft he made an arrangement so that it would raise and lower the bearing support on the shaft, resting this disk on the wheels of the locomotive, and hoisting it off when he did not want to wind the cable. That was, so far as I know, the original gathering locomotive, and is interesting in connection with the general development of the locomotives.

I agree with one speaker in regard to the question of terminals. A great improvement has been made on the controller terminals, and I think further improvement can be made in increasing the size of the terminals and the method of attaching the same in the resistances. Mr. Beers made some statements on that particular point. Personally, I advocate either a terminal soldered on to the end of the cable, or else a sleeve soldered to the end of the cable.

As to the question of air-gap, I mentioned before that the relative dangers due to the bearing going down are modified to some extent in the ball-bearing motor by reducing the air gap, and unquestionably this removes, to a great extent, the claimed advantages of the integrity of the air gap, if you do not keep the same air gap as is used with the sleeve bearing.

G. H. Shapter: Mention has been made of the storage battery locomotive as a future possibility in overcoming certain difficulties encountered in gathering work. It is true that quite a number of such machines have been installed. Some of these have been more successful than others, and for the most part the few failures noted have not been due to the locomotives or batteries, but rather to conditions existing in certain mines, such as flimsy tracks, lack of sufficient ties or spikes to properly hold the weight of the locomotive and prevent the rails from spreading, curves improperly laid, etc.

In one instance I had occasion to note a track laid ⅜ inch narrow, and as a natural result the locomotive was off track for an average of two hours per day. Now, to prove my point that conditions will be the obstacle that must be remedied, I will say that on the very next installation of a storage battery locomotive no trouble of the slightest character was experienced with derailment. The storage battery, in common with all other locomotives, must be provided with suitable rails in order to make their speed and increase the output.

Storage battery locomotives of a certain manufacturer are now operating successfully in coal mines, and range in capacity

from 500 lb. drawbar pull to 2400 lb., and speeds of 3½ to 5 miles per hour. The height varies from 27 in. to 46 in., and the width from gage plus 6 in. to gage plus 16 or 18 in., depending on whether inside or outside frames are used.

A careful study of the cost of operation, maintenance, repairs, power and attendance, etc., shows that a saving of from 30 to 35 per cent can be effected by the use of storage battery gathering locomotives as compared to mules. The calculations have been extended to a period of ten years and can be verified by actual results obtained in practise over a period of two years. The approximate estimated cost is four cents per ton-mile.

The segregated value of various items considered in the cost of operation of these storage battery locomotives is as follows:

	Alkaline	Lead
Interest on investment....	3.7 per cent	3.2 per cent
Depreciation and renewals of battery.....	9.0 " "	11.5 " "
Depreciation of locomotive	6.5 " "	11.5 " "
Battery incidentals.....	0.8 " "	0.85 " "
Electrolyte renewals.....	1.0 " "	0.00 " "
Locomotive repairs, oil, etc.	2.0 " "	2.15 " "
Motorman and helper.....	65.0 " "	70.00 " "
Power for charging.....	11.5 " "	5.40 " "

The relative values of the two totals are in the proportion of 94 per cent to 100 per cent, showing a very close margin. Cost of power does not enter greatly into the case even when figured at two cents per kw-hr., and for most isolated plants this extra power may be obtained during periods of light load on the generator without extra costs.

Personally, I do not believe storage battery locomotives can be as yet considered on an equal efficiency basis with trolley locomotives, perhaps never will be, but most certainly they will prove better than mules or some form of cable devices.

Apprehension may be felt on the score of durability and strength of the battery. I have seen cases with both the acid and the alkaline battery where the battery has been compelled to deliver power for pulling the locomotive onto the track after a severe derailment, which they did without any apparent bad results. The heavy current drawn under such conditions can well be imagined when I say it was necessary to hold the current breaker in by the foot.

C. J. E. Waxbom: I want to call your attention to a point with reference to the ball bearings, which I believe has not been brought out as yet, and that is, there is no wear to take place on the armature shaft with the use of ball bearings, and I think that is an important point.

E. H. Martindale: It has been pointed out in the discussion on this paper that a great deal of trouble is encountered on electric mine locomotives due to worn bearings. It has also been

pointed out that a large percentage of the commutation troubles can be traced to the unequal air gaps caused by the low bearings. It is rather surprising to note in this connection that the slotting of commutators, that is, undercutting the mica from between the copper bars of commutators on electric mine locomotives, has not gained headway more rapidly. At the present time I do not think that more than 10 per cent of the electric mine locomotive motors are operated with slotted commutators, while on street and interurban motors probably 95 per cent of the commutators are slotted.

With the recent legislation in some districts compelling the mine owners to pay miners on the run-of-mine basis, it will be necessary for the operating department to cut down expenses wherever possible, if the mine owners are to continue to operate their mines profitably.

The slight saving in brush cost by the use of slotted commutators is of practically no consideration, the great reduction in cost being accomplished by the saving in commutation wear, reduction of flash-overs, and burned out armatures, and other commutation troubles. With an unslotted commutator on such severe service as the average electric mine locomotive motor, it is necessary to use a brush which has sufficient abrasive material to grind down high mica which is caused by the sparking which occurs under the severe conditions. This necessarily means a brush which is continually grinding the commutator, and the cost of a new commutator for a motor is usually more than the cost of the brushes that will be used on the motor for ten years.

The slotted commutators will permit the use of a high-conductivity, low-friction, non-abrasive brush, and the sparking which will be caused by unfavorable conditions, such as the worn bearings, will not have the serious effect upon the commutator and will show a very great reduction in maintenance charges. With slotted commutators, however, it will be necessary to have careful inspection at regular intervals to prevent coal dust, carbon dust or other foreign materials from collecting in the slots and causing short circuits.

N. W. Storer: There is one point brought out that I feel I am able to discuss, and that is in regard to the efficiency and ventilation of the motor. One gentlemen made the statement that ball bearings enabled the air gap to be greatly reduced in the motor—that is probably true, from a mechanical standpoint; and if it were desirable to use the minimum air gap possible with mechanical clearances, every motor would be built with that minimum air gap; that is, the minimum air gap for the particular type of bearing in use. Such is not the case, as every one knows. One motor may have one-eighth inch clearance, another one-quarter, or five-sixteenths, or three-eighths inch—it depends on the electrical characteristics that are to be obtained with the motor. It is not simply a matter of efficiency, either, in reducing air gaps. I think in a great many cases you increase the effi-

ciency of the machine by increasing the air gap. When a motor has an extremely small air gap, it is liable to have far more losses induced in the pole faces than it would have with a larger air gap and corresponding increase in the turns on the field, necessary to overcome the larger air gap. It is a case of having the air gap to get the commutating characteristics that you want, as a general rule, not simply to get sufficient space for the armature to turn in.

Now, in regard to ventilation; it is perfectly true, what Mr. Stone has said, that one window out of five makes little difference on the motor, but there is no question at all about the fact that a motor under a box, even though it may be wide open underneath and have small openings on top, is going to run a great deal hotter than one which has holes on the sides as well as the bottom and top. We know from experience that a railway equipment with a motor well surrounded by the truck, will run a great deal hotter than one which is more exposed, in fact, that a motor that is on the head end of a truck will run cooler than the one on the rear end of a truck. That has been tested out time and again. There may be 10 or 15 deg. difference in temperature between the motors on the same truck, depending on the location, whether leading or trailing.

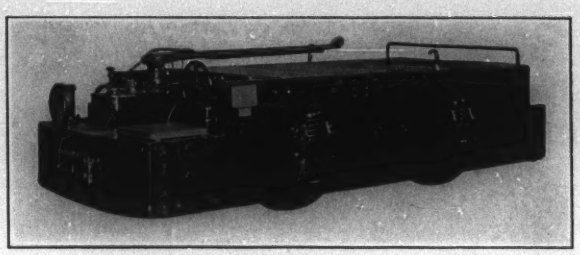
G. M. Eaton: Mr. Beers asked a question about split versus solid gears. The split gear is at best only a makeshift, though often it seems unavoidable. If the operator has a small shop with no press, it is tremendously tempting to apply a split gear. It is easy to renew, and has to be renewed. As everybody who uses them knows, there are more or less troubles with the split gears. I say that, representing a company which sells a great many split gears. The company with which I am connected always recommends the use of solid gears, where possible.

With regard to the use of hard gears, they are surely coming in mine locomotive work. The use of the split gear has until recently made the use of a soft gear essential.

It is only recently that hardened split gears have been used, but they are now produced commercially by various manufacturers. They are expensive, but they make up for the increased cost by their long life.

Mr. Beers also called attention to the need of co-operation between the users and builders of electrical machinery. He struck the keynote of development. The more of such co-operation, the better.

"Safety first" is of vital importance. I regret that the discussion of this principle has been all from the side of the manufacturers, because although the manufacturers keep in the field, to a certain extent, they do not live day and night with the machines. The real proof of the safety of a given type of machine is its actual performance, and this record must come from the operator. Safety first must be observed, not only from the standpoint of the designer, but from the standpoint of the education of the men in the mine, that, as far as possible, the men



TEN-TON ROLLED-STEEL SIDE-FRAME LOCOMOTIVE [STONE]

must be made to realize where their lives are in danger. This is true, regardless of the apparatus used.

The storage battery locomotive which requires tracks better than those found by experience to be practicable and commercial, is doomed to failure. The storage battery locomotive must be adapted to existing conditions.

F. L. Stone (by letter): The question of open frame versus closed rolled steel plated I think is worthy of a little further discussion. In the first place, the mine locomotive of the future will be as indestructible as it is possible to make it. It must be able to withstand severe collisions and frequent derailments without injury. The open frame locomotive Mr. Eaton advises had its inception in the main line railway locomotive. This type of large locomotive is built for high speeds and is not designed to withstand collisions or derailments. There are many other stresses which they have to withstand, which do not necessarily enter into the design of the mine locomotive. Steel castings of the shape shown are at best of questionable strength, due to shrinkage stresses. I note Mr. Eaton says the frame can be repaired with comparative ease by either electric welding or by the thermit process. I do not know just how much significance to attach to this statement.

In regard to the stability and strength please contrast Figs. 8 and 18 with the rolled plate side frame shown herewith. I believe it is impossible to construct a locomotive that will withstand the severe conditions of mine service better than the rolled plate side frame locomotive. There are possibly some slight advantages to be gained by the open frame when it comes to renewing brake shoes, etc., but I do not believe Mr. Eaton would recommend the abandoning of the locomotive pit even though nothing but open side frame locomotives were installed in the mine.

The question of miners riding while standing on the frames should be further emphasized. Mr. Eaton advises that if they do ride they are liable to lose their toes, or be hurt against the mine rib. They will surely ride if there is a place for them to stand on and in all probability will get hurt.

In regard to the cooling due to the open frame it is not fair to contrast the mine locomotive with the high-speed railway locomotive, or to draw conclusions from one and apply them to the other. I have seen many schemes of ventilation fail, notwithstanding the fact that they look perfect on paper. When tests have been made, and evidently they have not as yet, I would be pleased to hear the results. Finally, a locomotive of a given drawbar pull must have a weight in proportion thereto. There cannot be a better place to put this weight than in the side frames. If it is placed outside the wheel base the tendency is to make a "rocker", which is very liable to leave the track should there be any unevenness in the roadway. I have seen this rocking so bad that it was almost unsafe to run the locomotive.

must be made to realize where their lives are in danger. This is true, therefore, of the apparatus used.

The storage battery for motors which requires better than those found by machinists to be practicable and commercial, is doomed to failure. The storage battery locomotive must be adapted to existing conditions.

F. E. Stone (by letter). The question of open locomotives versus closed ones seems related. I think in worthy of a brief history discussion. In the first place, the rule for operation of the future will be as unmistakable as it is possible to make it. It must be able to withstand severe collisions and increased derailments without injury. The open frame locomotive Mr. Eaton advises had its inception in the main line railway locomotive. This type of large locomotive is built for high speeds and is not designed to withstand collisions or derailments. There are many other reasons which they have to withstand, which do not necessarily enter into the design of the tram locomotive. Now, I may be of the shape shown or at least of practicable strength, the to eliminate screens. I note Mr. Eaton says the frame can be repaired with compressed air by rather electric welding or by the thermit process. I do not know how much strength reference to attach to this statement.

In regard to the stability and speeds, please contrast Figs. 8 and 15 with the radial plate side frame shown beneath. I believe it is impossible to construct a locomotive that will withstand the severe conditions of mine service better than the radial plate side frame locomotive. There are possibly some slight advantages to be gained by the open frame when it comes to removing brake shoes, etc., but I do not believe Mr. Eaton would recommend the abandoning of the locomotive by even though nothing but open side frame locomotives were installed in the mine.

The question of motors riding while standing on the frames should be further emphasized. Mr. Eaton advises that if they do, the they are liable to lose their toes, or be hurt against the mine rib. They will surely ride if there is a place for them to stand on and in all probability will get hurt.

In regard to the cooling due to the open frame, it is not fair to contrast the mine locomotive with the high-speed railway locomotive, or to draw conclusions from one and apply them to the other. I have seen many schemes of ventilation fail, notwithstanding the fact that they look perfect on paper. When tests have been made, and actually they have not as yet, I would be pleased to hear the results. Finally, a locomotive of a given diameter will must have a weight in proportion thereto. There cannot be a better place to put this weight than in the side frames. If it is placed outside the wheel base the tendency is to make a 'moment' which is very liable to leave the track when the locomotive is in the roadway. I have seen this happening so bad that it was almost unsafe to run the locomotive.

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MINE SUBSTATIONS

Motor-Generator Sets vs. Synchronous Converters

BY WILL M. HOEN

ABSTRACT OF PAPER

The number of mines which use electrical power supplied by transmission lines carrying high-voltage alternating current is constantly increasing. Low-voltage direct current is usually required for underground work in all coal mines. These conditions require the installation of motor-generators or synchronous converters. The extent and location of the mine workings will determine the voltage of the direct-current supply. Improper application of the transforming apparatus may result in great variation of voltage in the direct-current network, with its attendant disadvantages.

The operating characteristics of the induction and synchronous motor-generator sets and synchronous converters are considered with regard to starting conditions, d-c. regulation and the effect on the a-c. transmission lines, a-c. voltage regulation, and power factor correction.

Mine conditions and the nature of the power supply will determine the type of transforming apparatus which will give the most efficient and satisfactory operating conditions. Each of the several types of apparatus has a field where the best results will be obtained.

DURING the past few years there has been a great increase in the number of mines, especially coal mines, using power supplied from the mining company's central power plant, or by central stations. Several central stations have recently built, and others have greatly extended their distribution, with the main object of serving mining districts. These conditions are making economical power possible for all kinds of mines. To provide economical transmission, this power is generally distributed at a voltage which requires transformation before it can be utilized in rotating machinery. Operating conditions at the average mine are such that direct current is required, and this requires the installation, as part of the mine equipment, of a motor-generator set, or a synchronous converter. The object of this paper is to show the adaptability and field of each type as applied to mine service.

In the small coal mine, where power for haulage service will

be a chief requirement, it is generally necessary, because of the mine location and layout, to feed power from the extreme end of the feeder system. Under these conditions, to avoid installing an excessive amount of copper and in order to maintain a reasonable voltage in the region of the maximum load, an increase in the terminal voltage of the d-c. generator becomes necessary with the increase in load.

However, when the mine workings become extensive, the low voltage generally used makes it desirable to feed into the feeder system at its load center, or even into two or more such places. This is sometimes accomplished by installing a substation underground, or in shallow mines, which are in favorable locations, on the surface, feeding the low-voltage current underground through boreholes. Under these conditions, an economical feeder system can be installed, so that the drop is low, and an increase of terminal voltage with an increase in load is not so necessary or desirable. As the mine system becomes larger, the amount and size of the apparatus will increase so that motors in constant load service, such as pumps and mining machines, will be distributed throughout the mine, to whose successful operation an excessive variation of voltage will be detrimental.

A direct-current motor, when subjected to an excessive increase in voltage, will have its shunt coils overheated, and its speed will increase, which will, with certain characteristic loads, overload the motor.

An excessive reduction in voltage will cause over-heating of the armature, reduced speed and reduced output. Series motors are generally used for intermittent service, and, as the torque is a function of the current, lower voltage will mean a greatly reduced speed and an increase in the time for any particular cycle of operation. This will invariably result in overheating of the motor windings.

Power for mine service is nearly always purchased on a unit basis and is easily and accurately measured. The actual cost of power is, therefore, accurately known, which is quite different from the former conditions, where each mine was usually served by an individual power plant where the actual cost of power was very indefinite. Due to the ease of ascertaining the actual cost, the mine operator is vitally interested in the over-all efficiency of the transforming apparatus.

The average mine is served with three-phase, 60-cycle power, at a voltage which is rarely higher than 11,000. Expert at-

tendance is not available or desirable. The first cost must be kept at a minimum, with the operating efficiency at a maximum. Direct current is required at a voltage generally under 300, but never exceeding 550. The selection of the proper apparatus lies between a motor-generator set, of the induction or synchronous type, and a synchronous converter. The starting characteristics of the last two types of machines have been very greatly improved, and the operation of the starting greatly simplified, within the last few years. The starting conditions of these machines in the order of their desirability follow:

1. Induction motor-generator.
2. Synchronous motor-generator.
3. Synchronous converter.

The induction and synchronous motor-generator sets consist of two machines, a motor and a generator, each electrically and magnetically independent. The generator can be given any reasonable characteristics, but standard practise is to flat-compound for 500 or 250 volts, or to over-compound not to exceed 10 per cent. The operating characteristics of the direct-current generator are understood by the average mine attendant, as its operation is similar to engine-driven generators with which he may be familiar.

The induction motor-generator set is exceedingly easy to start, but has the disadvantage of a small air gap and a lagging current characteristic, which causes the transmission line to carry an additional current above the required load current. This means an increase in the transmission line and power station generator capacity.

The synchronous motor-generator set of the present day is no more difficult to start than the induction motor set. It has the advantage of a large air gap and the power factor of the machine is under the control of the operator. This latter feature, if properly applied, is of great benefit to the transmission line regulation. If induction motors are in use at the same mine, operating the synchronous motor at a leading power factor will greatly offset the lagging wattless component. It requires judgment to secure the best results from this feature. While the corrective effects apparently only benefit the power company, they may be detrimental as well as beneficial, and in order that the power company may secure the greatest benefit, it would be necessary for the attendant to be under the control of the power company, as far as power factor adjustment is

concerned. Standard machines are usually built for operating at unity power factor at full load, and under average load conditions it is possible to operate them at slightly leading power factor without detrimental results.

It is now recognized that a low power factor load is detrimental to the power company, so that such loads are sometimes penalized, the power rate being based on the power factor. Under such conditions it is advisable for the mine operator to utilize the corrective effect of a synchronous machine, so as to offset the lagging effect of any induction motors. It is not always economical to attempt to raise the power factor too high, as the corrective effect obtained from a given wattless component is much less in the regions of unity power factor than elsewhere. Generally speaking a power factor of 90 per cent would be considered good. The efficiency of a synchronous motor will be materially affected

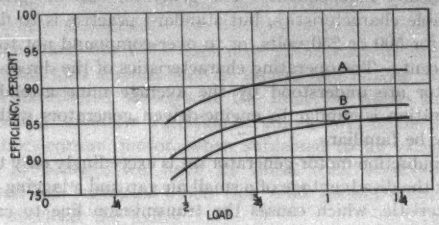

FIG. 1

by over-excitation. Reference to Fig. 1 will show the efficiency curve of a standard synchronous motor-generator set, as built by one manufacturer, when operating at unity and 80 per cent leading power factor.

Synchronous converters are nearly always started from the alternating-current end, and are no more difficult to start than in the preceding cases, except that it is necessary to close the field break-up switch, so that the direct-current polarity will be correct. They have the advantage of large air gaps, and each unit consists of one machine instead of two. The machine itself is much lighter, and requires less energy to bring it up to speed. The 60-cycle converter of today is quite a different piece of apparatus from that of only a few years ago.

Referring again to Fig. 1, curve *A* is the efficiency curve of a standard synchronous converter of the same rating as the motor-

generator set, with transformer losses included. A converter does not lend itself to power factor correction to the same extent as the synchronous motor. The disadvantage of using transformers will be offset by giving the machine a large decree of protection from grounds which might be caused by surges on the high-tension line. It is much easier to run, temporarily, on two transformers than to repair a high-voltage coil in either an induction or a synchronous motor.

A synchronous converter necessarily requires transformers, while both the induction and synchronous motors can be wound for moderately high voltages. Standard mine sets of less than 300 kw. are not wound for voltages in excess of 2200. Therefore, if the voltage is above 2200 transformers will be required in either case, or the machine can sometimes be wound for a higher voltage at an increased cost and reduced efficiency.

In contrast to a motor-generator set, the alternating-current and direct-current sides of a synchronous converter are connected together. The direct-current voltage bears an approximately constant ratio to the impressed alternating-current voltage. In a direct current generator, an increase in voltage with an increase in load is obtained by placing series coils on the field poles, which coils carry all or a portion of the load current. In the converter the same method is used, but the accompanying results are obtained quite differently. Standard synchronous converters are built so as to give flat compounding, maintaining approximately constant terminal voltage. As the direct-current voltage bears a definite ratio to the alternating-current voltage, it is necessary to maintain constant voltage at the collector rings. This is accomplished by having a suitable reactance and a certain minimum resistance in the alternating-current circuit. This reactance may be introduced separately or be in the transformer, line and generator. To maintain constant voltage, the line drop, due to resistance, must not be in excess of 10 per cent. Maintaining constant voltage with varying load by changing the series field excitation will change the power factor. The effect on the line, therefore, is quite different from that caused by a synchronous motor without compounding, as usually built. This results in the difference in corrective effect of the two types of machines. Over-compounded synchronous converters are not standard, because certain limitations peculiar to the type of machine make it undesirable.

In a synchronous converter, part of the alternating current

passes directly to the direct-current end, without circulating through the entire converter windings. The heating capacity of a direct-current generator will depend upon the average heating, while in a synchronous converter it depends upon the heating of the so-called tap coils. Low power factor at full load will cause heavy currents to circulate in the converter winding. As the tap coils must carry this heavy current in addition to the current passing through them, the heating will be above the average of the rest of the winding.

The average mine load, referring particularly to the direct-current load, is usually of a very fluctuating character. Assuming that the field of a synchronous motor is adjusted for unity power factor, say at $\frac{3}{4}$ load with constant excitation, the power factor will be leading at lighter loads and lagging at the heavier loads. A synchronous converter, as generally constructed with varying excitation caused by compounding, will act quite differently, provided, of course, that the line conditions are suitable. As the load falls below the $\frac{3}{4}$ value, the power factor will be lagging, and at full loads, and overloads, slightly leading. Where power is received at high voltages from large transmission lines, the capacity effect may make it more desirable to have a lagging component at light loads and leading at maximum loads. Under these conditions the synchronous converter will give the most desirable performance. However, where large corrective effects are required there is no doubt but that the synchronous motor is the type to be employed. When the synchronous motor receives its excitation from an over-compounded generator the exciting current will increase with the load, thus tending to hold the power factor up on overloads. The synchronous motor-generator set can be successfully operated on a line whose characteristics are such that the operation of a synchronous converter would be unsuccessful. Parallel operation between machines of the same type is practically on the same basis for each of the three types. Parallel operation between machines of the different types is not advisable, as considerable adjustment will be necessary to obtain equal division of the loads.

Cost. A comparison in prices between the induction, or synchronous, motor-generator set, and the synchronous converter, including transformers for the latter, will show that the costs are approximately the same when transformers are not required by the motor-generator set. It is the usual practise for the central station to supply power at 2200 volts, so that it is seldom neces-

sary for the coal company to purchase transformers. In smaller sizes the synchronous converter with its transformers will cost a little more than the motor-generator set, while with the larger sizes, the reverse is true. For the sizes most common for mine work, the motor-generator set will cost less than the synchronous converter with transformers.

The foregoing comparisons show that where the line characteristics are suitable, the operating efficiency and automatic alternating-current line regulation are in favor of the synchronous converter. Where large corrective effects are required on the alternating-current line, compounding is desired on the direct-current machines, and the transmission line characteristics are not of the best, the synchronous motor will prove the most reliable. When the voltage and frequency variations are such as to preclude the successful operation of synchronous apparatus, the induction motor-generator set should be used.

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MINE SUBSTATIONS

Their Construction and Operation

BY H. BOOKER

ABSTRACT OF PAPER

The use of electricity in mines has been making rapid progress throughout the United States. Steam and compressed air are being superseded largely by central station power. Power from a central station requires a substation to supply direct current to operate locomotives, cutting machines, etc. A substation is used to transform high-voltage a-c. power to direct current at 250 or 500 volts.

Substations, when possible, should be located on the surface, because if located underground there is danger from fire, and dampness weakens insulation and causes corrosion of metallic parts. Construction of an underground substation is more costly than on the surface, as there is danger of the roof giving way. The roof should be arched, or built of heavy concrete and the whole station made fireproof.

When substations are located underground it is necessary to carry a high-tension cable through bore-holes. When located on the surface a low-tension cable can be used.

Many accidents occur because of incompetent men. Good salaries should be paid and competent men obtained. Danger warnings should be posted and men taught to consider wires as being "live", thereby lessening accidents.

DURING the last few years the use of electricity in mines has attracted a great deal of attention throughout the United States. This is largely due to the large increase in coal consumption making it necessary to discard the early primitive methods of running and to install modern power equipment, without which it would be impossible to produce the required output with the present supply of labor.

Steam and compressed air have been and are still used to a large extent for the power supply at the coal mines, but there is a growing use of electricity especially during the last two or three years, due to the introduction of central station power which, strange to say, can be sold to a coal mine cheaper than the mine can produce it itself.

The greatest care should be exercised in the introduction of electric power in a coal mine and the very best advice should

be obtained before attempting any electrical installation about a mine. Electric power improperly installed and not properly operated and maintained will no doubt prove a hazard and it is just such conditions that is causing apprehension in some localities regarding the use of electric power in mines.

The danger and unsatisfactory service associated with electric power in the past, has been largely due to the short sighted policy of the coal mining companies in purchasing cheap equipment unsuited to the service and in employing incompetent labor.

A coal mine is the last place where inferior or poorly designed electrical apparatus should be used, as the risk of trouble is too great.

Even with the best designed and best adapted equipment the question of operation and maintenance is one that is often sadly neglected. The matter of compensation is often allowed to play too prominent a part, and the wages offered are such that it is impossible to obtain competent men who will take proper care of the equipment and who will realize the importance of properly maintaining the apparatus.

Rigid, systematic, and careful tests should be made periodically on all moving parts of electrical equipment to insure proper operation and records kept of these tests for future reference.

Warnings regarding the danger of touching wires cables or electrical apparatus should be from time to time pointed out to all workmen in the mine, and in some way kept constantly before them. The primary cause of the majority of accidents, it is fair to say, is partial or complete ignorance. Those unskilled in electrical work should treat all electrical apparatus as alive, as only in so doing lies complete security for them.

The writer proposes to deal with the installation, operation and maintenance of substations around coal mines from the standpoint of the practical operator. Until quite recently the electric power in use at coal mines was produced by small isolated plants located at each mine. With the large increase in production and the combination of many small mines, the central plant idea and the purchase of central station power is rapidly gaining ground.

The use of power from a central plant, or of purchased power, requires a substation to supply direct current to operate the mine locomotives, cutting machines, underground pumps and lights.

A mine substation, in general, consists of one or more motor-generator sets or synchronous converters used to transform high voltage a-c. power to direct current at 250 or 500 volts.

The small isolated plant was generally placed near the pit mouth, provided the coal and water supply was convenient. As the capacity of the mine increased and the distance to the working face became greater the power conditions became quite unsatisfactory. An increase in the capacity of the existing plant often means a large expenditure of time and money so that the purchase of central station power and the installation of a substation offers the best solution. The substation can generally be placed at a more advantageous point than the isolated plant since a substation is independent of coal and water supply. An increase in power supply at any time can be easily and quickly taken care of at a low cost.

Substations when properly designed and installed require little attention, and the attendant is needed only to reset circuit breakers and to see that everything is running properly. If power is not wanted the machines can be cut out and all expense for current stopped. Starting up is a simple matter of closing a switch and full power is available immediately.

With purchased power, the substation system of power distribution is most advantageous for coal companies operating singly or widely separated mines. The operator transfers his responsibility to those whose business it is to carry it, leaving him free to his business of mining coal, thus relieving him of the worry and care of his power plant, and thereby greatly increasing the efficiency of his coal mining department. The operator substitutes his power house with its engineers and firemen and its need for good and abundant water, with a small substation that requires only one attendant and no water supply.

The exact location of the substation is often a hard question to decide. Conditions frequently arise where it would be desirable to install the substation underground, but in general, unless absolutely necessary, the substation should be placed above ground. The preferable location is at the pit mouth when possible, as it can then be looked after by a workman who has other duties to perform. In a small mine the tipple foreman can attend to the station, while in a shaft mine the station should be located in the hoist room and looked after by the hoist engineer. In a large mine requiring more than

one station, they should be located centrally to the work to save the expense of heavy copper feeders. The substation can often be located near the fan so that the same operator can look after both. When the d-c. feed wires cannot be carried into the mine by one of the openings, bore holes can be used, as it is comparatively simple to maintain a 500-volt cable installed in a bore hole.

In regard to locating the substation underground there are many objections to this. Beside the source of danger from fire there is most always considerable dampness underground which not only weakens the insulation but causes corrosion of unprotected metallic parts. It is practically impossible to make an underground substation free from moisture, and good ventilation is often difficult to obtain. This matter of ventilation is very important as the heat losses in the apparatus must be carried away so that the capacity of the machines will not be impaired. This question will be readily appreciated when it is considered that one kilowatt loss per minute is equal to 57 B.t.u., which is equivalent to heating about 3001 cu. ft. (84 cu. m.) of air one degree fahr. per minute. The total loss in a 200-kw. station will be approximately 15 kw. The heat generated will, however, help to keep the substation dry in conjunction with proper drainage and pumping.

All underground substations should be ventilated with intake air and all high-tension cables should, when possible, be carried to the substation in the intake airway. This may work a hardship particularly if the mine is shaft operated and a blowing fan is used, as it is practically impossible to maintain wires in a shaft of this kind on account of the high air velocity. The writer knows of mines of this type where it is unsafe for a man to attempt to ascend the stairway, much less do any work while the fan is in operation.

Very often considerable coal dust and pure sand is picked up by the air currents which is a rather severe matter, as the dust and sand plays havoc with the bearings and oiling systems.

A very important point regarding the construction of an underground substation is the cost of construction, which is considerably greater than building on the surface. Since there is always danger of the roof giving way, the roof should be arched or built of heavy reinforced concrete and the whole station made fire proof. For a 200-kw. substation the dimensions should not be less than 24 by 24 by 12 ft. (7.3 by 7.3 by 3.6 m.) high.

With the substation located underground it is generally necessary to carry a high-tension cable through a bore hole. With the station located on the surface this cable will be a low-tension cable and there will be no trouble to maintain it. A satisfactory method is to use "lead" covered cable attached to a messenger cable about every 30 feet by wiped joint or suitable clamps which will not injure the lead. The high-tension cable is much more difficult to maintain, and most mine electricians know what it means to maintain high-tension insulated cable in deep shafts and in bore holes.

The question of attendance for an underground substation is a serious one and actual experience has taught the writer that it is impossible to get men underground to give machinery the same attention they will give it on the surface. This is particularly true of the night shift, as it has been found that there is a greater tendency among men to sleep on the night shift in mines, than on the same shift outside. This may be due to the mine atmosphere, which is often contaminated with gas from gob workings.

In regard to the general design and construction of a mine substation, space economy should be given consideration, but care must be exercised to see that there is plenty of room for making repairs and replacements.

The operating requirements of a substation in regard to continuous service may vary from a few hours per day to practically continuous service. As due provision must be made for inspection and repairs it is quite evident that in case of continuous operation, attention must be given to the proper sectionalization of the apparatus and duplication of the equipment.

A very important point to consider is the relative attention that will be given to the operation of its station by the consumer and the central station company. It is only natural that the consumer will want to supervise the operation of his own station so that it is evident that any complications in switching equipment and control apparatus should be avoided.

The substation should be constructed of fireproof material, and all high-voltage apparatus should be enclosed to secure maximum safety to attendants. Asbestos lumber should be used for partitions and doors, which serves as a protection against shock and is a valuable protection in case of fire.

The common faults in electrical installations of this kind are as follows:

Exposure of high and medium pressure conductors at the surface and high and medium pressure switching gear underground.

The frames of high and medium pressure apparatus not properly grounded. All machine frames should be well grounded.

Switches, cables, rheostats, starting boxes, etc., mounted on wood and surrounded by as much wood as possible, the whole often resulting in two occurrences; first, a shock by coming in contact with an exposed live part; second, fire due to defective joints in cables.

Omission of tubes, where frames of machines and brattices are pierced by cables.

The common defects of organization are as follows:

The absence of trained electricians.

The handling of live wires or apparatus for adjustment or repair when not absolutely necessary.

The absence of a definite and distinct rule that unskilled men may handle electrical cables and apparatus only when the power is off.

The use of central station power will no doubt bring the operating force at the mine in close touch with the central station operating force which is always ready and willing to advise the coal operator in regard to his installation and operation.

It is to be hoped that improved legislation and a better cooperation between the mining companies and the Bureau of Mines will greatly increase the safety and improve the operating conditions in connection with the use of electricity in mines.

DISCUSSION ON "MOTOR-GENERATOR SETS VS. SYNCHRONOUS CONVERTERS IN MINE SUBSTATIONS" (HOEN), AND "MINE SUBSTATIONS; THEIR CONSTRUCTION AND OPERATION" (BOOKER), PITTSBURGH, PA., APRIL 10, 1914.

W. A. Thomas: Unquestionably from the standpoint of economy the synchronous converter is superior to the motor-generator set, but in a careful analysis of the mining conditions, and the ultimate results to be accomplished, the question of the kilowatt-hours per ton in transformed energy constitutes a relatively small proportion of the total cost. The method of distribution of the direct current which has been converted has a great bearing on this question. As pointed out in Mr. Hoen's paper, the energy in the small mine is carried through one opening which is the main entry, and when the bituminous mine, particularly, as distinguished from the anthracite mine, comes to the commercial condition requiring electric haulage, the power is mainly consumed some distance from the entry. The distance of the point of consumption from the mine entry in the average bituminous field is probably upwards of a mile.

This gives rise to the necessity of over-compounding in order to maintain a fairly constant voltage at the point of consumption, and even at that it is not practicable to put in a distribution of copper in the mine to maintain much less than 10 per cent variation in voltage at the point of consumption.

It is for this reason that the motor-generator set is undoubtedly more popular in mining work than the synchronous converter, and this is particularly true of the bituminous mines, where large areas are worked out due to the thinness of the coal. There is, however, a field for the synchronous converter where several openings are served from one station, in which case a flat voltage is desirable. The question of efficiency of the converter over the motor-generator set is offset, to some extent, by the introduction of the over-compounding, so that at maximum load the losses due to the 10 per cent higher voltage transmission are less than on the flat compounding with the corresponding load on the station.

A particular point of advantage in the synchronous motor-generator set as brought out by Mr. Hoen is the power factor correction, and in this connection there is an interesting development which I think is followed by practically all manufacturers at the present time, and particularly in the low-voltage motor-generator set, of exciting the synchronous motors from the over-compounded generator, so that the field adjustment of the synchronous motor is made for good power factor at light load, and the 10 per cent over-compounding of the generator compensates for the increased load on the synchronous motor by bringing up its field excitation. That is being given study, and the suggestion has been made that in the use of 500- to 600-volt sets where a separate exciter is necessary similar results

can be obtained by one of two methods, either to put a series winding, auxiliary to the shunt winding, on the field of the exciter, the current in which shall be proportional to the load on the direct-current generator, so that in a similar manner the exciter voltage is brought up with the load on the set; or, another, and perhaps a more advantageous way of doing this is to excite the field of the exciter from the generator so as to get the benefit of the over-compounding by raising the excitation on the shunt field of the exciter. This would prove to be advantageous, doubtless, in railway work, as well as where the loads are greatly fluctuating, and where it would not, perhaps, be advantageous to run the excitation of the synchronous motor at maximum at all loads.

P. M. Lincoln: I have always felt pretty strongly about this matter of synchronous converters as compared with motor-generators where the problem is simply one of transposing alternating current into direct current. I have always felt that the synchronous converter had so many advantages over the motor-generator that there was no question about it. There are certain disadvantages, of course, connected with the synchronous converter when it is used. One of these disadvantages is that it is impossible to give it a high over-compounding, and if over-compounding is essential to the use of direct current in mines, that simply means that the synchronous converter is not available.

While I am rather familiar with the apparatus used, yet I will have to confess I am not at all familiar with the actual conditions that exist in mines, and so I am unable to express an opinion on the necessity of this very high over-compounding, which seems to be the general reason for demanding motor-generators rather than synchronous converters for mining work. The only thing that makes the motor-generator more applicable and better adapted to that duty is, as I said before, the necessity for that high over-compounding. If you can get away from the necessity for high over-compounding, I do not think there is any question, in general, that the synchronous converter will be much better for the purpose of getting the direct-current supply than any other piece of apparatus.

N. Stahl: Much of the emphasis of the superiority of motor-generator sets to synchronous converters for mine operation is laid on the over-compounding feature. As Mr. Lincoln has pointed out, it is undesirable, but not impossible, to over-compound the synchronous converter, even for cases where the rise only amounts to 10 per cent at full load. The difficulty arises from the fact that so large an amount of reactance is required; so that practically it leaves an undesirable feature on account of the excessive currents which flow in the tap coils of the converter at high load when you have a considerable amount of leading power factor current. The advantage, however, of the higher voltage procurable by the over-compounding of the motor-

generator can largely be eliminated by the very simple device of operating your converter at as high a flat-compounding voltage as you will get at the full-load condition on the over-compounded generator. Inquiry develops the fact that both the synchronous converters, now standard for mine work, and the motors standard for mine work, are applicable for this higher voltage condition under light load, so that excessive bucking or flashing or commutation trouble is not to be expected. That being the case, the argument in respect to the average voltage on the direct-current line is in favor of synchronous converters, which permits a comparison more or less on the basis of the curves presented in Mr. Hoen's paper, which show, for a load, on the average, of three-quarters full load, about 7.5 per cent advantage in favor of synchronous converters, plus transformers, over the synchronous motor, running without transformers; but, bear in mind that in many cases transformers will also be required with the motor-generator, which will make the discrepancy still greater in favor of the synchronous converter.

If you evaluate for a particular case of an average synchronous converter substation capacity of 200 kw., on the basis of three hundred working days of ten hours each, and a load factor of 25 per cent—which presumably might be much better, particularly if advantage is taken of the present tendencies in design to construct machines which will carry safely 200 per cent overload for such length of time as is necessary for the accelerating of trains—you will find, on a one cent per kw-hr. basis, there will be a difference in cost of power per year of about $160, which represents about 6¾ per cent of the presumptive first cost of substation equipment which, by Mr. Hoen's figures, are placed at about a parity, with a tendency, however, towards an initial cost preference in favor of the converter and transformers, over the motor-generator alone, as the capacity increases.

The question of the power factor correction by the two devices has been raised. Mr. Thomas brought up the point that by the automatic over-compounding of the excitation of the synchronous motor directly from the generator or otherwise, through an exciter—which, by the way, increases the cost of the motor-generator set—much of the inherent automatic tendency of the converter toward a movement of the power factor through lagging values, at no-load, toward leading values at high load, may be secured on the motor-generator. To that no exception can be taken, so far as it goes. There is, however, an inherent tendency on the part of the operating man not to over-excite his machine, regardless of his instructions; that is, if his machine is operating on the basis of 80 per cent leading power factor at full load, the tendency is to get it as close to unity as possible, and let it stay there, or else under-excite the machine, on the mistaken notion that over-excitation

would force the field too hard, thus making the system power factor worse instead of better.

While there is no question of the ability of the synchronous motor, properly handled, to effect better conditions at the power house, taking them as they are under present conditions, yet the integrated values for the ordinary set will show, I think, a predominating influence in favor of the synchronous converter.

W. A. Thomas: From a theoretical standpoint, the contention of Mr. Stahl is absolutely correct, but when we take into account the fact that the connected apparatus on a substation ranges from 50 to 180 per cent over the capacity of the substation, and the fact that the average load factor of such a substation is about 35 per cent of its capacity, we have a condition in which with constant voltage, motors which are attached to that line are subjected to an over-voltage. In other words, if we take the voltage which is now practically standard in coal mining service, namely, 275 volts in one class, and 600 volts in the other class, we find the apparatus, the commercial motors, for pump driving, fan driving, and for cutting machines, ranged from 210 to 250 volts. The industrial motor, so-called, for driving pumps and fans, is standard at 230 volts. It is true you can get motors wound to 250 and 275 volts, on their fields, but it means ordering these motors specially, as no standard of this character has been established which is carried in stock.

In the buying of a pump, for instance, the proposition is taken up with a pump manufacturer, and he buys a motor from the local stock of the manufacturer with the result that he gets a standard motor of 230 volts in the low-voltage class, or 500 volts in the medium-voltage class. The result is that when he has a flat voltage of 275 or 500 volts and when the load is light on the station, he will get the full voltage of the circuit on his motor field. This is also true of the night cutting of coal, where the load is relatively small, unless an adjustment is made of the voltage at the power station with a flat-compounding system. That adjustment, in the case of a converter substation, requires either a regulator or a shifting of the voltage taps applied to the synchronous converters. It is for these reasons, mainly, that in the installation of substations the use of the motor-generator predominates.

N. Stahl: There is one point in connection with the converter substations which should be mentioned. The use of synchronous converter substations in mines necessitates the use of two banks of transformers, in the event of the power being fed in at higher voltage than 2200. One bank would be necessary for feeding the local mine circuit and the other bank for feeding the synchronous converters. That adds to the first cost.

Will M. Hoen: From personal experience in metal mines, where the conditions are better than in coal mines, I think an underground substation, particularly in a coal mine, should always be avoided if possible.

In regard to motor-generator sets and synchronous conver-

ters, the intention was merely to show that the electrical work being done in mines nowadays is better than it was a few years ago. Formerly one generator was put in the mine entrance, copper was stretched through the mine, and things gradually grew on to the system. Nowadays, in the better class of mines, with the use of substations, their location and the distributing system can be advantageously planned; so that the question of using excessively over-compounded voltages should become of less interest. It undoubtedly is true that the majority of the substations have motor-generator sets, and use over-compounded voltages. This requirement is generally necessary on account of locomotives which require direct-current. Although a large amount of copper may be installed, the track circuit is in bad condition, and this generally accounts for the large voltage variations.

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MAGNETIC AND OTHER PROPERTIES OF ELECTROLYTIC IRON MELTED IN VACUO

BY TRYGVE D. YENSEN

ABSTRACT OF PAPER

Electrolytic iron of a purity of 99.97 to 99.98 per cent was melted in fused magnesia crucibles in a modified Arsem furnace, forged into rods, machined, and annealed in an electric furnace according to various heat cycles.

The magnetic properties were obtained by the Burrows double bar method. Determinations were also made of the electrical resistance, chemical composition, and physical properties, including microstructure and critical temperatures as well as tensile tests. A few commercial iron and steel samples were tested for comparison.

The following valuable results were obtained:

1. Pure iron melted in an atmosphere of carbon monoxide under atmospheric pressure will absorb both carbon and oxygen with the result that the iron thus produced is of an inferior magnetic quality.
2. Low-carbon iron melted in vacuo will lose 50 to 90 per cent of its original carbon content.
3. The magnetic quality of electrolytic iron melted in vacuo is decidedly superior to any grade of iron thus far produced, the maximum permeability obtained being 19,000 at a flux density of 9500 gausses. The average hysteresis loss obtained is less than 50 per cent of that found in the best grade of commercial transformer steel, due to the fact that the coercive force is very much lower than for silicon steel, although the retentivity is higher.
4. The specific electrical resistance of pure iron melted in vacuo is 9.96 microhms per centimeter cube.
5. Swedish charcoal iron melted in vacuo has a magnetic quality approximating that of electrolytic iron melted in vacuo, chiefly due to the reduction of the carbon content.

The author suggests that the high electrical conductivity and hence large eddy current losses in this material may possibly be greatly reduced by the addition of silicon or aluminum without very materially affecting the magnetic quality.

PREVIOUS to the beginning of the twentieth century Swedish charcoal iron was the best grade of iron that could be found for magnetic purposes. About that time Hadfield[1] produced a number of iron alloys that revolutionized the iron industry so far as magnetic iron was concerned. His 2.5 per cent silicon alloy and 2.25 per c nt. aluminum alloy showed

a higher permeability and gave a lower hysteresis loss than the purest Swedish iron. Perhaps even more important was the high electrical resistance of these alloys, reducing the eddy current loss to one-third or less of that of the Swedish iron under identical conditions. At the same time Barrett[2] showed that the increase in electrical resistance due to the addition to pure iron of one per cent of any alloying element is inversely proportional to the atomic weight of that element.

Since the time of the appearance of Hadfield's alloys comparatively little improvement has been made in the magnetic quality of the iron and iron alloys. What has been done has mostly been in the way of modifications of Hadfield's silicon steel. In 1906, however, Professor C. F. Burgess[3] of Wisconsin commenced a series of investigations upon the magnetic and allied properties of electrolytic iron and its alloys with other elements. While the improvement made by Burgess were not revolutionizing, his investigations, I think, have pointed out the direction in which improvements may be expected. In 1910, E. M. Terry[4], also of Wisconsin, investigating the effect of temperature upon the magnetic properties of electrolytic iron as deposited, found that this iron, after annealing at 1100 deg. cent. and slow cooling, has a very high permeability and a low coercive force. On account of its high retentivity, however, the hysteresis loss was found to be higher than for Swedish charcoal iron.

In 1911 the writer commenced an investigation of the magnetic properties of iron in the Electrical Engineering Department of the University of Illinois. Doubly refined electrolytic iron, deposited according to the methods used by Burgess, has formed the basis for the investigation. It was deposited from Swedish charcoal iron, of the following composition:

C	0.163 per cent
Si	0.032 " "
S	0.0002 " "
P	none
Mn	none
Fe (by difference)	99.8 " "

1. Barrett, Brown and Hadfield, *Jour.* Inst. Elec. Engrs., Vol. 31, p. 674, 1902.

2. *Proc.* Royal Society, Vol. 69, p. 480, 1902.

3. See *Electrochem. & Metal Ind.* for 1909 and 1910. A series of articles by Burgess and Aston.

4. *Phys. Rev.*, Vol. 30, p. 133, 1910.

The doubly refined iron contains:

C	0.006	per cent
Si	0.01	" "
S	trace	
Fe (by difference)	99.98	" "

The crucibles used were made from electrically fused magnesia containing about two per cent silica, and these crucibles were placed in graphite crucibles and securely covered. At first a

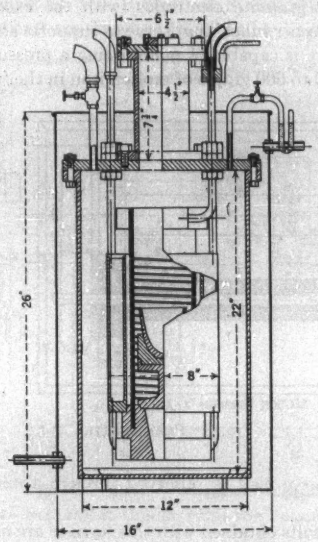


FIG. 1—VACUUM FURNACE

Hoskins resistance furnace was used for the melting of the iron but this was abandoned after a large number of attempts had been made to keep the iron from being contaminated. If the crucibles were left exposed in the furnace the iron was so badly oxidized that it cracked to pieces under the hammer in the attempt to forge it. If buried in crushed carbon the iron absorbed comparatively large quantities of carbon. Burgess used the latter method and found that the iron absorbed from 0.05 to 0.15 per cent carbon, probably by reducing the carbon monoxide

gases surrounding it. The results obtained by the writer agree with those obtained by Burgess, so far as the carbon is concerned, but as will be shown later, carbon alone does not account for the properties of the iron thus produced.

In order to overcome the difficulties above referred to, a vacuum furnace was constructed in the shops of the department. It is modeled after the Arsem type of furnace, and is shown in Fig. 1 and Fig. 2. The inside parts consist entirely of graphite cut from solid graphite electrodes, with the exception of the water-cooled copper tubes, that serve as supports as well as leads. A Geryck pump is capable of maintaining a pressure of 0.5 cm. or less with 500 to 600 grams of molten iron in the furnace. The

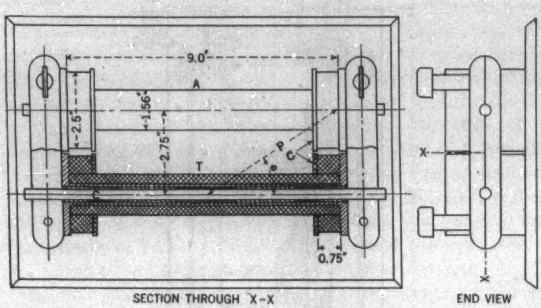


Fig. 3—Permeameter

state of the charge may be observed through a mica window in the top.

While the results obtained with this furnace are not as uniform as might be desired, it must be remembered that the tests have necessarily been made upon relatively small samples, that the processes involved in order to obtain the test pieces in the final condition are numerous, and that the magnetic properties of this material are very readily affected by outside influences. The chemical composition of the final iron is quite uniform.

Method of Magnetic Testing

A number of different instruments for the magnetic measurements were tried and discarded. The main defect of most of them was that large and uncertain corrections had to be made to

the readings in order to arrive at the correct results. As it was desirable to make a large number of test pieces, Rowland's ring method was impracticable on account of the difficulty of construction, and also because of the difficulty of electrical resistance measurements. An instrument was needed that could measure accurately the magnetic properties of relatively short rods. The one finally decided upon was constructed by the writer in the shops of the department in accordance with the recommendations of the Bureau of Standards.[5] The details of this instrument[6] are shown in Fig. 3 and a diagram of the con-

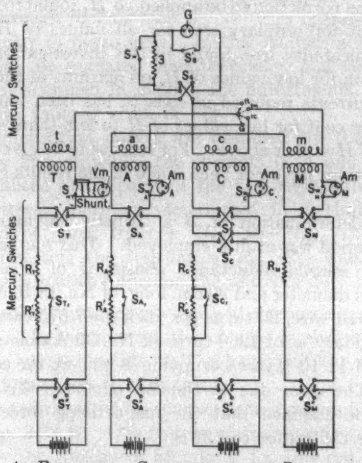


FIG. 4—ELECTRICAL CONNECTIONS FOR PERMEAMETER

nections in Fig. 4. Briefly stated, it consists of a double bar and yoke with one main solenoid T, and one auxiliary solenoid A, separately controlled, and four compensating solenoids, C, next to the yokes connected in series. Each of these coils was wound with No. 18 B. & S. gage double-cotton-covered wire in 10 layers of exactly 20 turns per inch ($=7.875$ turns per cm.). By means of the three secondary coils, t, a and c, the magnetic flux

5. *Bulletin*, Bureau of Standards, Vol. 6, No. 1. Reprint No. 117.

6. For further information regarding the various apparatus and instruments here described, the reader is referred to Bulletin No. 73 of the Engineering Experiment Station of the University of Illinois.

can be investigated at different points of the magnetic circuit and equalized by adjusting the currents in the magnetizing coils. With no leakage of flux, the magnetizing force for the rod measured is

$$H_T = 0.4\pi\, n_T\, I_T$$

where n_T = number of turns per cm. of main solenoid,

I_T = current in main solenoid in amperes.

This is strictly true if the effects of the ends of the various magnetizing coils are negligible. These end effects have been calculated and the correction to be applied to H_T found to be less than +1 per cent for ordinary iron for all values of H. For the highest permeability iron found in this investigation, however, the correction for low values of H, on account of the high compensating currents required in coils C, has been found to vary from +4 per cent for low values of H to less than +1 per cent for values of $H = 8$ or above. For reasons to be given presently, these corrections have not been made in the results given in this paper.

For the determination of B a ballistic galvanometer of a 15-second period was at first employed. This was calibrated by means of a mutual inductance, consisting of a primary coil, M, 10 cm. in diameter and 90 cm. long, of No. 18 B. & S. double-cotton-covered wire, 20 turns per inch (=7.875 turns per cm.), with a secondary m, of 1260 turns of No. 30 double-silk-covered wire, wound in 10 layers occupying 8 cm. at the center of the primary. The error due to the end effects of this coil is such that if it be assumed that the magnetizing force H_M at the center of the calibration coil M is

$$H_M = 0.4\pi\, n_M\, I_M$$

then the values found for B_i of the rod tested are high by 0.3 per cent.

The ballistic galvanometer served the purpose very well until the electrolytic vacuum iron was ready to be measured in the annealed state. On account of the high permeability and low electrical resistance of this iron, the change of magnetism was found to be too sluggish for accurate determinations with a ballistic galvanometer. This was particularly true for hysteresis determinations. Five or six seconds were sometimes required for the flux to complete the change, so that by

the time the galvanometer coil had reached its maximum deflection the flux was still changing. It was, therefore, very evident that the galvanometer had reached its limit of usefulness, even though its period had been doubled.

To overcome this difficulty a Grassot fluxmeter was used for all the final measurements. In this instrument the suspension effect has been practically eliminated, and its deflections are independent of the time required by the flux to complete the change.

All the different connections for operating the permeameter are made through rocking mercury switches operated by means of keys similar to piano keys. In this manner any number of switches may be operated simultaneously, and comparatively little time is occupied in making the adjustments. A view of the operating table is given in Fig. 6.

The magnetization curves are obtained by the method of reversal, by first adjusting the currents in A and C until the flux is equalized at all parts of the magnetic path.

The hysteresis loops are determined in a similar manner, but instead of going from $+H_{max}$ to $-H_{max}$, the change is made by inserting the resistances R'_T, R'_A, and R'_C in the magnetizing circuits by opening the switches S_{T_1}, S_{A_1} and S_{C_1} either alone or simultaneously, with the reversing switches S_T, S_A, and S_C. In this manner the change is always made from H_{max} to the various points on the loop, and the effect of the viscosity of the iron is eliminated.

In Fig. 5 are shown three magnetization curves for the standard rod, No. 3-33 B. One is drawn according to the certificate supplied by the Bureau of Standards for this rod. The other two were obtained by the writer, in one case by using the Grassot fluxmeter and in the other by means of the ballistic galvanometer. There is some doubt as to the case of the discrepancy for low and medium densities between the curve as obtained by the Bureau and that obtained by means of the fluxmeter. On this account the corrections above referred to have not been made, as the writer feels that, if his results be slightly in error, the error is on the safe side.

Details of the Experiments

The electrolytic iron previous to being placed in the crucible to be melted was crushed into small pieces and thoroughly cleaned with hydrochloric acid, boiling distilled water, and

alcohol. It was then transferred to the crucible, covered with a magnesia cover and placed in the vacuum furnace. The furnace was exhausted immediately and heated up, slowly at first, so as to give the absorbed gases time to escape without too much loss of vacuum. With the furnace at a dull red heat the melting would then require about ½ hour with an input of 15 kw. In order to insure homogeneity 12 kw. was left on for another 15 minutes and the furnace then allowed to cool.

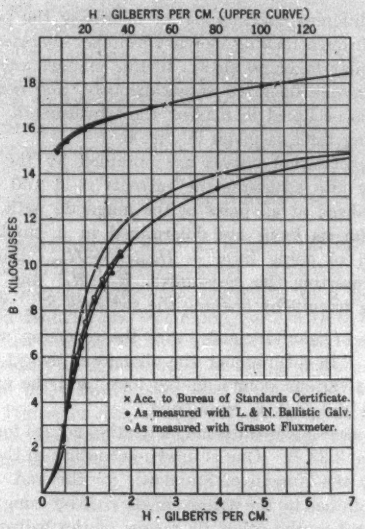


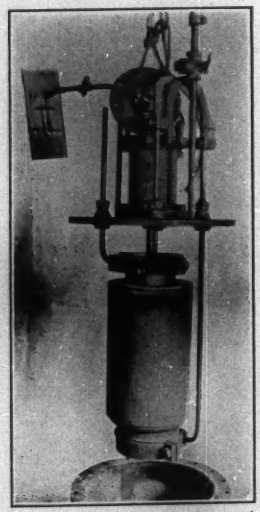
FIG. 5—MAGNETIZATION CURVES FOR STANDARD ROD NO. 3-33B

When removed from the furnace the ingots were as bright as silver and so soft that they could be cut with a knife. They were reheated in a coke forge to ordinary forging temperatures, 1000 to 1100 deg. cent., and forged into rods about ½ in. by 20 in. (1.25 by 50 cm.).

From these rods the following test pieces were prepared:

1. The magnetic test piece, serving also for the electric tests, 0.392 in. (0.996 cm.) in diameter and 14 in. (35.5 cm.) long.

2. Two test pieces for the mechanical tests. These had a



[YENSEN]

FIG. 2—VACUUM FURNACE, INSIDE VIEW

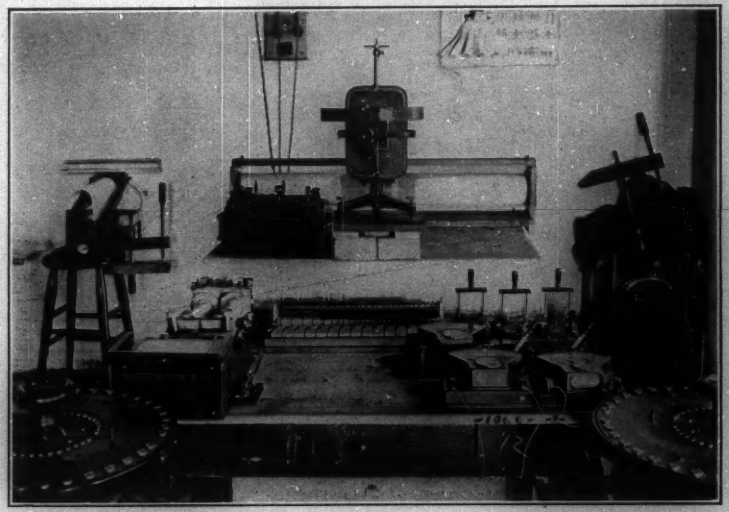


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FIG. 6—OPERATING TABLE FOR MEASUREMENTS WITH PERMEAMETER

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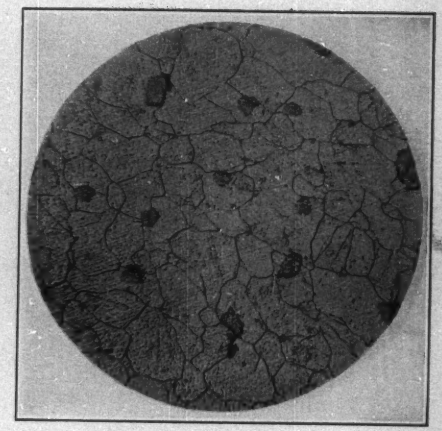
FIG. 7—ANNEALING FURNACE



[YENSEN]

FIG. 13—ROD NO. 3-39A, AS FORGED; ELECTROLYTIC IRON MELTED IN VACUO. MAGNIFIED 60 DIAMETERS

middle section 0.3 in. (0.76 cm.) by 1½ in. (3.8 cm.), with threaded ends, ½ in. by ½ in. (1.25 cm.).

3. One test piece for the study of the microstructure, ½ in. by ½ in. (1.25 cm.).

4. One test piece for the critical temperature determination.

For the chemical analysis the shavings obtained from the preparation of these test pieces were collected, after first removing the outside coating of oxide.

After being tested as forged, the test pieces (1 and 3 above) were sent through different heat treatments. If they were to be annealed they were packed in pulverized magnesia in an iron cylinder, *A*, and placed in the annealing furnace shown in Fig. 7. In order to minimize the formation of oxide the magnesia was moistened with alcohol to drive out the air. After reaching the annealing temperature desired, the cooling was done, in all but the preliminary tests, in accordance with definite cooling curves. The temperature was measured by means of a platinum-platinum +10 per cent rhodium pyrometer, calibrated from time to time.

Quenching was done by placing the test pieces in the cylinder *Q*, Fig. 7, filled with magnesia and moistened with alcohol. When the desired temperature was reached, the cylinder was removed from the furnace, tipped up, and the contents plunged into the quenching bath by means of a sharp blow on the top of the cylinder.

As mentioned above, a small specimen was prepared for the critical temperature determinations of each rod. These determinations were made by placing the specimen in a ½-in. (1.25-cm.) "electroquartz" pyrometer tube, with the hot junction of the pyrometer inserted in the small hole made in one end of the specimen. The tube was partly filled with fused magnesia and placed in a Hoskins muffle furnace with the end at the middle of the furnace. The temperature was gradually raised to about 1000 deg. cent., the current cut off and the furnace allowed to cool naturally, while the time interval for each 10 deg. cent. was obtained by means of two stopwatches. From the data thus obtained three different curves were plotted for each specimen, namely, (1) the temperature-time curve, using temperature as abscissa and time as ordinate; (2) the temperature-rate curve, using temperature as abscissa and the number of deg. cent. fall in temperature per minute as ordinate; (3) the temperature inverse rate curve, using temperature as

abscissa and number of seconds per deg. cent. fall in temperature as ordinate. From these curves the critical temperatures can readily be located.

While this method is not as accurate as the differential method by means of three thermocouples, it serves as a check upon the other determinations made in the course of the investigation.

From the chemical analysis of the Swedish charcoal iron and the doubly refined electrolytic iron it is seen that the only mea-

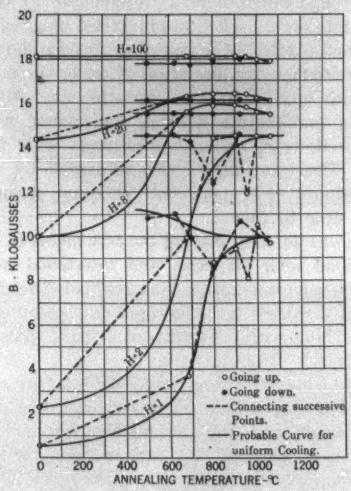


FIG. 8—EFFECT OF ANNEALING TEMPERATURE UPON PERMEABILITY, ROD NO. 3-39

surable impurities in the latter are carbon and silicon. As these are the only impurities that are liable to be affected during the processes described, it seemed superfluous to analyze for anything except carbon and silicon. A few analyses were made for sulphur, but only traces could be found.

All the rods tested have been analyzed for carbon by direct combustion. On account of the small quantities dealt with, extreme care had to be used in these analyses.

Results

The results of the investigation are embodied in the following tables and figures. In order to ascertain the most favorable

TABLE I.
SUMMARY OF RESULTS
Rods Thoroughly Annealed at 900 Deg. Cent.

Rod No.	Description of iron	Furnace used for melting	Carbon as per chemical analysis, per cent	Max. permeability	Flux density for max. perm.	Hysteresis loss, ergs per cu. cm. per cycle		Coercive force for $Bm =$ 15000	Retentivity for $Bm =$ 15000	Spec. elect. resist. at 20° C. microhms	Crit. temp Ar_3 deg. cent.
						$Bm =$ 10000	$Bm =$ 15000				
3-38	Electrolytic	Vacuum	0.0104	19000	9500	813	1640	0.295	12100	10.0	905
3-39	"	"	0.0110	16500	8500	880	1860	0.32	12600	9.95	905
3-34	"	"	0.0090	16000	6500	895	1600	0.30	10600	10.2	895
3-49	"	"	0.0120	15400	5000	902	1710	0.31	8100	9.9	
3-31	"	"	0.0120	13100	6200	980	1760	0.32	9100	10.03	885
3-43	"	"	0.0196	12900	5500	1165	2180	0.40	10200	9.85	895
3-48	"	"	0.0080	12600	5500	955	1850	0.29	9300	9.7	
3-36	"	"	0.0150	12250	6000	953	1830	0.33	9000	10.16	875
3-40	"	"	0.0110	12000	9000	1240	2500	0.36	10100	9.7	895
3-47	"	"	0.0080	11900	8000	1190	2120	0.35	9000	10.05	900
3-50	"	"	0.0099	11600	5000	995	1940	0.30	9000	9.7	
3-41	"	"	0.0095	11250	4500	1155	2180	0.40	10000	10.0	895
3-30	"	"	0.0090	11050	5500					9.94	
3-45	"	"	0.0080	10500	9000	1470	2640	0.40	10600	9.87	895
3-37	"	"	0.0450	8050	4500	1255	2000	0.40	9500	10.3	885
Avg.	"	"	0.0125	12950	6550	1060	1990	0.34	9940	9.96	894
Avg. for Iron melted in resist. furnace			0.1000	1965	3930					13.53	
3C01	0.05%C added	Vacuum	0.0130	8600	6000	1405	2300	0.40	10000	10.24	895
3C02	0.10%C added	Vacuum	0.0120	7600	7000	1710	3190	0.50	10700	10.64	895
3C03	0.50%C added	Vacuum	0.1810	4400	5500	1910				12.40	
1-21	Sw. charc. iron remelted in vacuum		0.0080	10350	7000	1290	2640	0.48	11200	10.30	
Commercial Grades											
SwI-4	Sw. charc. iron cut from plate.		0.1630	4870	6600	2490	4530	0.95	8000	10.57	
G1&2	Stand. transformer steel*			3850	7000	3320	5910	1.33	9900	11.09	
H1&2	4 per cent silicon steel.*			3400	4300	2260	3030	0.88	5400	51.15	

*Received manufacturer's standard anneal.

annealing temperature, one of the rods, No. 3-39, was annealed at a number of different temperatures ranging from 500 deg. to 1060 deg. cent., in every case followed by a natural cooling of the furnace. The result is shown graphically in Fig. 8.

Based upon the results obtained with No. 3-39, the 15 rods made from electrolytic vacuum iron were tested after various heat treatments. The final heat treatment received by all of the rods consisted in annealing at about 900 deg. cent. and cooling in 48 hours according to a straight time-temperature curve, connecting 900 deg. and 200 deg. cent. To give the details of the results obtained after the various treatments, would be beyond the scope of this paper, and only the final results can be included. In Table I the rods have been arranged according

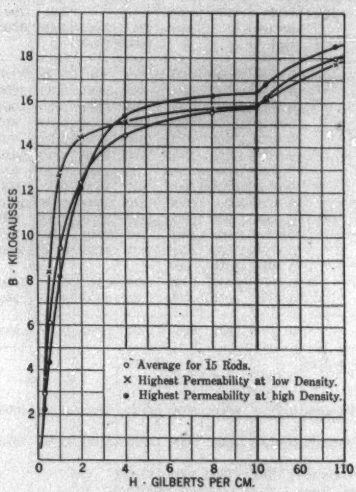


FIG. 9—AVERAGE AND HIGHEST MAGNETIZATION CURVES FOR ELECTROLYTIC IRON MELTED IN VACUO

to the maximum permeability obtained for each rod, and this shows the hysteresis loss and other magnetic data, as well as the carbon content of the rods and their electrical resistance. The last column gives the critical temperature Ar_3 whenever measured. Fig. 9 shows the magnetization curves for the average and best electrolytic vacuum iron, and Fig. 10 shows the hysteresis loops and permeability curve for the best rod, No. 3-38.

For the sake of comparison a number of other rods have been

tested and the results included in this paper. Sw.I-4 is a rod cut from a plate of Swedish charcoal iron, and No. 1-21 is made from iron cut from the same plate as Sw.I-4 and directly next to it, but remelted in vacuo. No. 3C01, No. 3C02 and No. 3C03 are three rods made from electrolytic iron with additions of 0.05, 0.10 and 0.50 per cent carbon, respectively, and melted in vacuo. G-1 and G-2 are two rods made from such commercial bars as are generally rolled into sheets known as "standard electrical sheets." H-1 and H-2 are rods made from bars containing

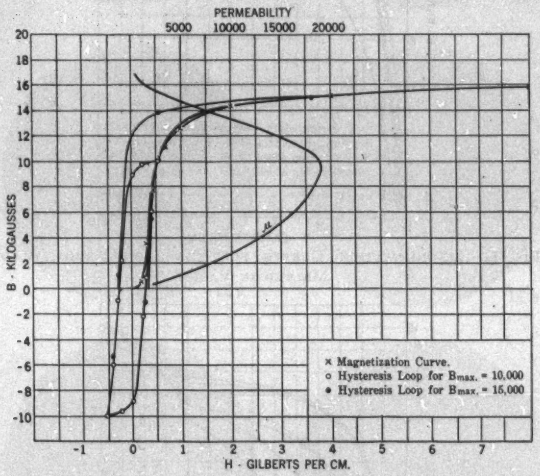


FIG. 10—HYSTERESIS LOOPS AND PERMEABILITY CURVE FOR ROD NO. 3-38, ANNEALED AT 900 DEG. CENT., COOLED IN 48 HOURS

about 4 per cent silicon. These two sets were supplied by the manufacturers and have received their standard anneal. They are supposed to represent good commercial steel used for electrical machinery. Table I also includes some information with regard to the properties of the electrolytic iron as melted in the resistance furnace. Figs. 11 and 12 show the magnetization curves for all the rods, compared with the average for the electrolytic iron melted in vacuo, all after having received the final heat treatment. The results of the mechanical tests are shown in Table II. A few of the photomicrographs are exhibited in

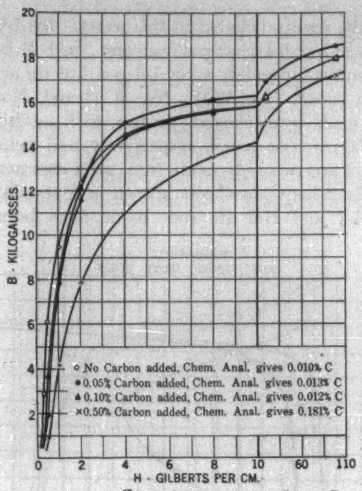


FIG. 11—MAGNETIZATION CURVES FOR THE IRON-CARBON ALLOYS, MELTED IN VACUO

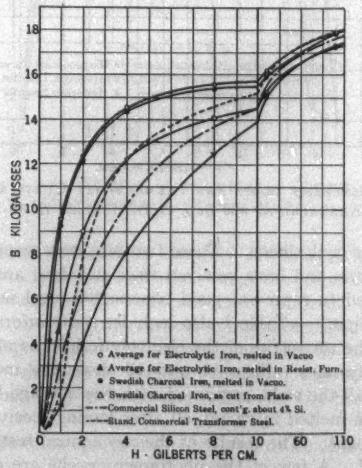
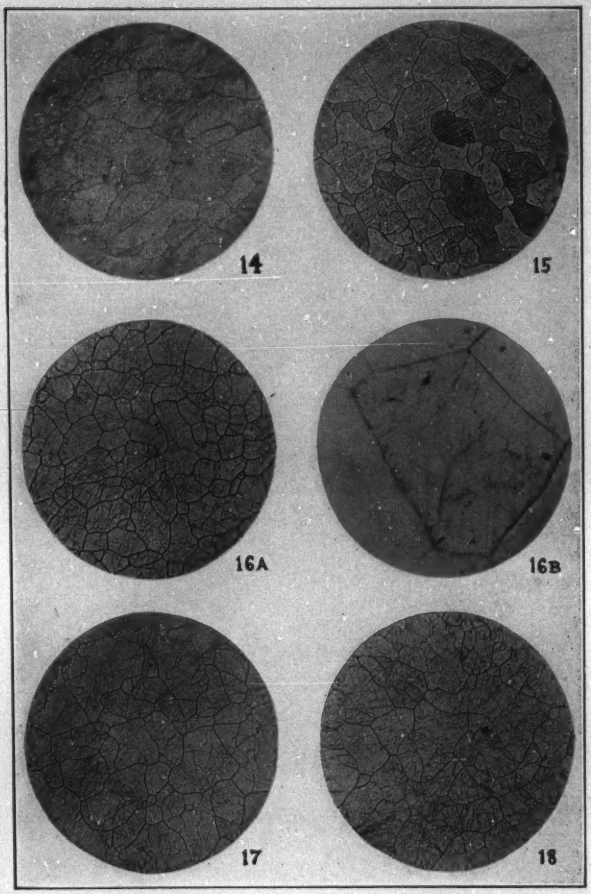


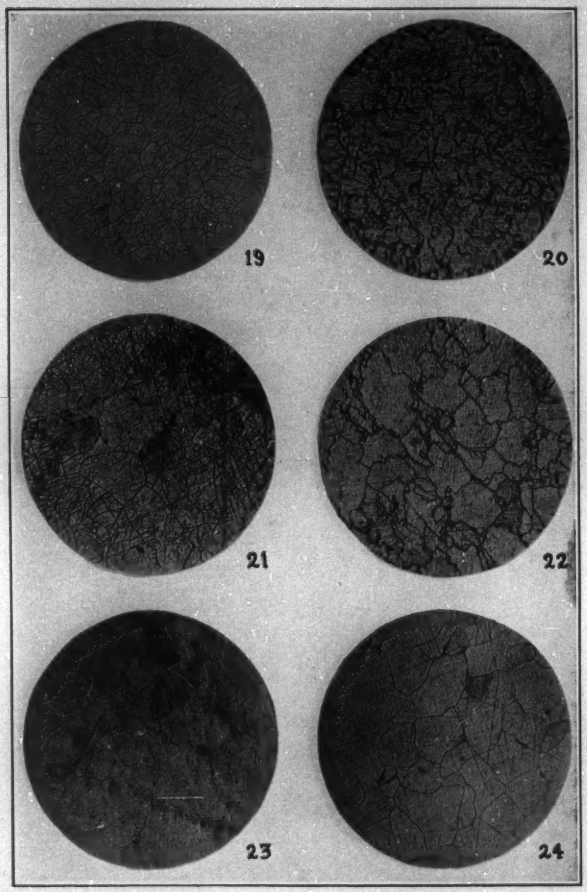
FIG. 12—COMPARISON OF MAGNETIZATION CURVES FOR DIFFERENT GRADES OF IRON



[YENSEN]

ELECTROLYTIC IRON MELTED IN VACUO

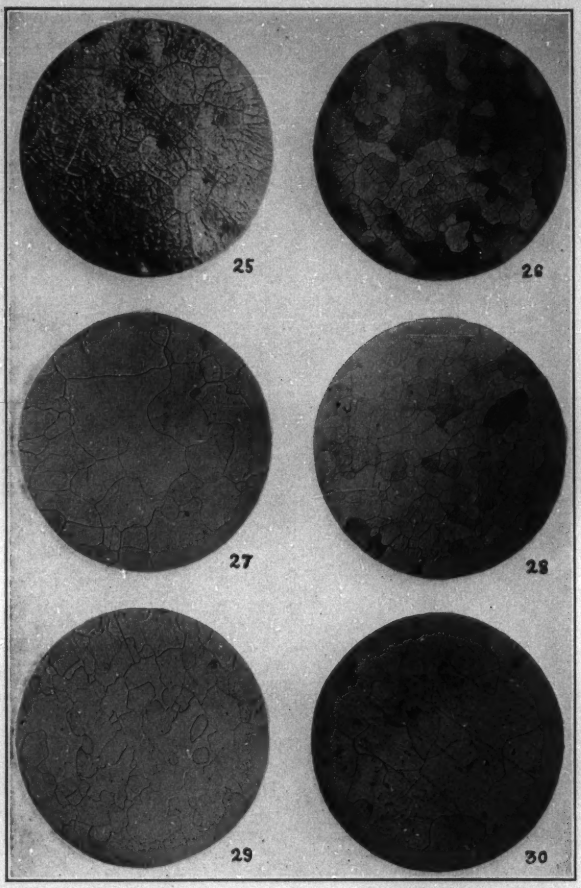
FIG. 14—No. 3-39B; annealed at 680 deg. cent. going up. 40 diam.
FIG. 15—No. 3-39D and E; annealed at 900 and 950 deg. cent. going up. 40 diam.
FIG. 16A—No. 3-39F; annealed at 1000 deg. cent. going up. 40 diam.
FIG. 16B—Same sample as in FIG. 16A, magnified 240 diam.
FIG. 17—No. 3-39G; annealed at 1060 deg. cent. going up. 40 diam.
FIG. 18—No. 3-39J; annealed at 800 deg. cent. going down. 40 diam.



[YENSEN]

ELECTROLYTIC IRON MELTED IN VACUO

FIG. 19—No. 3-39L; annealed at 616 deg. cent. going down. 40 diam.
FIG. 20—No. 3-39O; quenched from 1000 deg. cent. in brine. 40 diam.
FIG. 21—No. 3-39S; annealed at 900 deg. cent., cooled in 48 hours. 40 diam.
FIG. 22—No. 3-31A; as forged. 40 diam.
FIG. 23—No. 3-31K; annealed at 900 deg. cent., cooled in 48 hours. 40 diam.
FIG. 24—No. 3-36C; annealed at 900 deg. cent., cooled in 24 hours. 40 diam.



[YENSEN]

FIG. 25—No. 3-38D, electrolytic iron melted in vacuo; annealed at 900 deg. cent., cooeld in 48 hours. 40 diam.

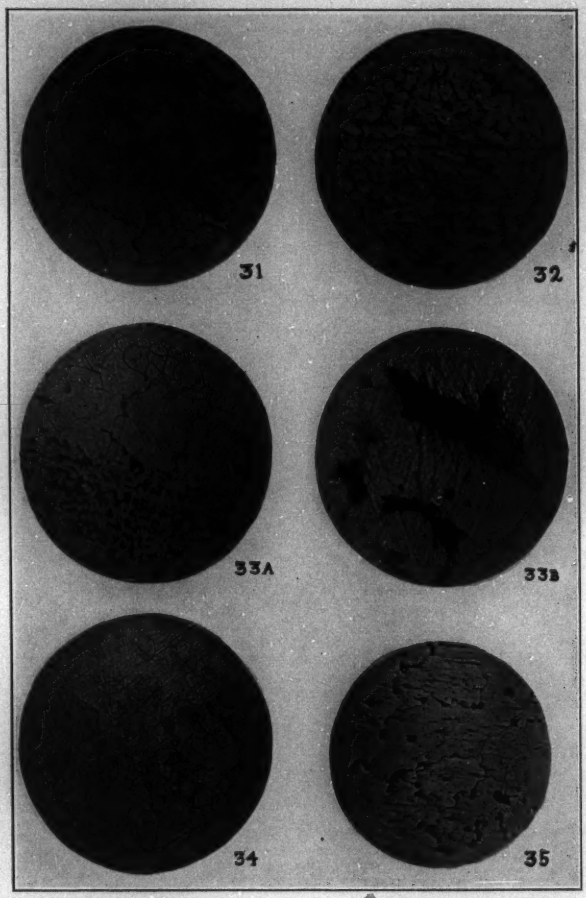
FIG. 26—No. 3-41B, electrolytic iron melted in vacuo; annealed at 900 deg. cent., cooled in 12 hours. 40 diam.

FIG. 27—No. 3-43B, electrolytic iron melted in vacuo; annealed at 900 deg. cent., cooled in 12 hours. 40 diam.

FIG. 28—No. 3-45B, electrolytic iron melted in vacuo; annealed at 900 deg. cent., cooled in 12 hours. 40 diam.

FIG. 29—No. 3-47B, electrolytic iron melted in vacuo; annealed at 900 deg. cent., cooled in 12 hours. 40 diam.

FIG. 30—No. 3C01D, electrolytic iron with 0.05 per cent carbon added, melted in vacuo; annealed at 900 deg. cent., cooled in 48 hrs. Analysis shows 0.013% carbon. 40 diam.



[YENSEN]

FIG. 31—No. 3C02D, electrolytic iron with 0.10 per cent carbon added, melted in vacuo; annealed at 900 deg. cent., cooled in 48 hours. Analysis shows 0.012 per cent carbon. 40 diam.

FIG. 32—No. 3C03D, electrolytic iron with 0.5 per cent carbon added, melted in vacuo; annealed at 900 deg. cent. Analysis shows 0.181 per cent carbon. 40 diam.

FIG. 33A—No. Sw. I-4B, Swedish charcoal iron cut from plate; annealed at 900 deg. cent. 40 diam.

FIG. 33B—Same sample as in FIG. 33A, magnified 240 diam.

FIG. 34—No. 1-21A, Swedish charcoal iron remelted in vacuo; as forged. 40 diam.

FIG. 35—No. 3-13C, electrolytic iron melted in resistance furnace under atmospheric pressure; annealed at 900 deg. cent. 40 diam.

TABLE II.

Summary of Results of Mechanical Tests

Spec. No.	Carbon content %	A: As forged					B: Annealed from 900° to 200° C. in 12 hr. accd. to straight line.					C: Annealed from 900° to 200°C. in 24hr.acc'd.to log. curve exc. as noted					D: Quenched in brine from 1000°C. except as noted					Remarks
		Stress at yield point lb. sq. in.	Ultimate strength lb. sq. in.	Elong. % 1*	Elong. % 2†	Red'ct of area %	Stress at yield point lb. sq. in.	Ultimate strength lb. sq. in.	Elong. % 1*	Elong. % 2†	Red'ct of area %	Stress at yield point lb. sq. in.	Ultimate strength lb. sq. in.	Elong. % 1*	Elong. % 2†	Red'ct of area %	Stress at yield point lb. sq. in.	Ultimate strength lb. sq. in.	Elong. % 1*	Elong. % 2†	Red'ct of area %	
3-30	0.0090	36,600	44,800		41	87.7																
3-31	0.0120	69,100	70,500		20	82.8	20,700	35,500	30	60	89.5											
3-33		64,000	68,000		22	81.5												40,500	24	53	84.5	
3-34	0.0090												34,300		47	61.1		55,500	14	32	83.1	
3-35												14,400	34,500		54	87.3		44,900	22	44	86.0	
3-36	0.0150											20,100	37,500		52	77.0						
3-37	0.0450																41,250	64,600	15	37	73.7	
3-38	0.0104												35,150		56	85.5	37,400	45,500	17	42	86.1	
3-39	0.0110	35,800	44,700		39	80.4						16,400	36,100		61	80.9						Column C annealed in 48 hr. according to straight line.
3-40	0.0110	39,600	43,500		38	82.3		41,600		42	85.7											
3-41	0.0095	62,200	65,500		26	83.8		40,200	18	53	85.1											
3-43	0.0096						18,750	35,800	31	59	84.5											
3-45	0.0080	51,400	55,500		32	85.8	15,000	39,400	27	40	88											
3-47	0.0080						17,400	36,100	31	57	91.3						30,200	40,000	20	47	80.8	
																	15,500	35,400	27	45	36.6	Quenched in liq. air.
3-48	0.0080	45,600	51,800	12	36	86.4						15,300	35,800	23	42	73.2						Column C annealed 900° to 200° C. in 24hr. acc'd. to straight line.
3-49	0.0120	41,400	48,700	12	44	76.2						11,100	34,900	23	32	75.7						
3-50	0.0099	38,200		12.5	35							19,300	35,800	28	45	86.5						
Avg.	0.0125	48,390	54,800	12.2	33.3	83.0	17,960	38,100	27.4	51.8	87.4	16,100	35,500	24.7	48.6	78.4	36,280	50,170	18.6	42.5	82.4	
3C01	0.0130						21,000	51,100	27	41	72.5						33,200	53,000	20	65	86.2	% carbon added = 0.05
3C02	0.0120						19,400	38,900	29	60	73.5						67,700	76,900	7	25	79.7	" " " = 0.10
3C03	0.1810						22,100	51,000	24	50	64.5											" " " = 0.5
SwI-4	0.1630		40,000		36	57.0																As cut from plate.

*Elongation before specimen has commenced to "neck." † Ultimate elongation.

Figs. 13-34, including most of those obtained for rod No. 3-39, as this rod received more heat treatments than any other rod. This series for No. 3-39 may be studied in advantage in connection with Fig. 8. Figs. 30 to 32 show the effect upon the microstructure of adding carbon to the iron, and Figs. 33 and 34 show the difference between Swedish charcoal iron before and after being remelted in vacuo. The structure of the electrolytic iron melted in the resistance furnace is shown in Fig. 35. Fi-

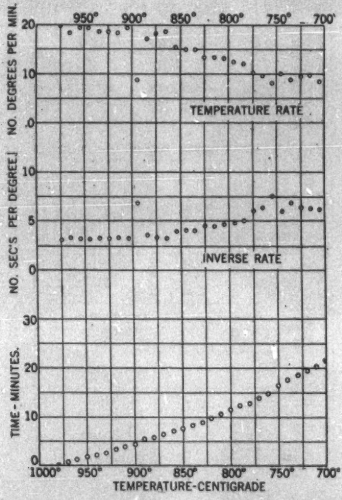


FIG. 36—COOLING CURVES FOR ROD NO. 3-43

nally, Fig. 36 is a sample cooling curve for the critical temperature determinations.

DISCUSSION OF RESULTS

The results obtained may perhaps best be discussed by considering first the equilibrium diagram for iron-carbon alloys. Fig. 37 shows this diagram as represented by Rozenhain.

This diagram should probably be modified somewhat in view of the recent researches upon the critical temperatures for pure iron. It has been shown, for instance, by Burgess and Crowe,

in a bulletin just issued by the Bureau of Standards, that the point F, usually called Ar_2, for pure iron is 768 deg cent. Furthermore, it has been shown conclusively that the temperature at which pure iron changes from a ferromagnetic to a paramagnetic substance or vice versa, is 785 deg. cent., thus showing that these two transformation points do not coincide.

Only that part of the diagram lying to the left of I will be considered here. From this diagram it is seen that after the iron has passed from the liquid state it exists in the form of a solid solution of iron and carbon, called austenite. When this solution cools it eventually reaches the line $E\ G\ I$, where ferrite crystals begin to be precipitated. Upon further cooling

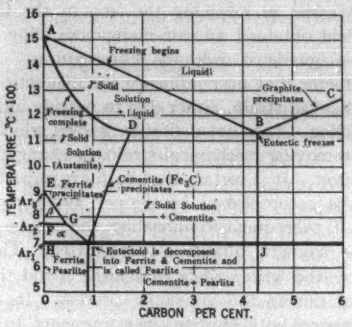


FIG. 37—EQUILIBRIUM DIAGRAM FOR IRON-CARBON ALLOYS, ACCORDING TO ROZENHAIN

the solution, now enriched in carbon, passes downwards towards the right, following $E\ G\ I$, more and more ferrite being precipitated. Finally, upon reaching the point I, the part of the solution still remaining, containing now 0.9 per cent carbon, is decomposed into cementite (Fe_3C) and ferrite, and the resulting mixture is called pearlite. At this temperature the iron consequently consists of pure ferrite crystals with the spaces between the crystals filled up with a mixture of ferrite and cementite. One generally-accepted theory states that iron has three different allotropic modifications: Alpha, Beta and Gamma. Gamma iron is stable above the line $E\ G\ I$, Beta iron between $E\ G$ and $G\ F$, and Alpha iron below $G\ F$. It has been shown that iron in the

Beta and Gamma modifications is weakly paramagnetic, while Alpha iron is ferromagnetic. Under certain conditions Beta and Gamma iron may exist to some extent below the boundaries just stated. It is supposed, for instance, that if iron be cooled rapidly from a high temperature, Gamma and Beta iron may not have sufficient time to change into Alpha iron. If, however, such iron be reheated to above the line *E G I* and slowly cooled, the iron may ultimately all be obtained in the ferromagnetic Alpha modification. This theory is confirmed by the results obtained by Hadfield and Hopkinson, who found that the "specific magnetism" of iron-carbon alloys is decreased to a large but uncertain extent by quenching from a high temperature. Certain elements, carbon and manganese for example, when added to the iron assist in retaining the iron in the Gamma form. Thus Hadfield obtained an iron-manganese alloy that is practically non-magnetic at ordinary temperatures.

Another factor that may influence the magnetic properties of iron is mechanical strain, either due to outside influence or due to rapid cooling. It is not definitely known which is the more important, removing mechanical strain, or changing all the iron into Alpha iron. It is certain that both are important and that both may be accomplished by proper annealing. It is well known that if, subsequent to annealing, the iron be mechanically strained, its magnetic quality is depreciated. This point was confirmed by the writer while measuring a rod that had been slightly bent during the annealing process. Its permeability seemed, compared with previous measurements, to be unusually low. It was noticed that in clamping it in the permeameter it had been strained to some extent. It was then adjusted so as to lessen the strain as far as possible, and the permeability was found to have increased materially. This fact helped to explain some rather puzzling results previously obtained in the course of the investigation. It also showed that, if the iron has not been strained beyond a certain point, the effect of the strain is only temporary.

With the above explanations and facts in mind, the results given in the previous part of the paper will now be considered.

It is at once apparent from Table I that the melting of electrolytic iron, or low-carbon iron in general, in an atmosphere of carbon monoxide gases, gives the iron a chance to absorb carbon, the amount absorbed varying from 0.05 to 0.15 per cent. This result is in agreement with the experiments of Burgess and Aston

referred to in the introduction. It is furthermore seen that carbon is not the only factor that affects the magnetic properties of iron. Swedish charcoal iron, Sw.I-4, with a carbon content of 0.163 per cent, and 3C03, an electrolytic iron-carbon alloy melted in vacuo, with a carbon content of 0.181 per cent, both have a decidedly higher permeability than the electrolytic iron melted in the resistance furnace, although the latter has an average carbon content of only 0.10 per cent. Again, the electrical resistance of the resistance furnace iron is 13.52 microhms while that of Sw.I-4 and 3C03 is 10.57 and 12.40 respectively. The carbon content of 0.1 per cent does not by itself account for a resistance of 13.52 microhms. According to Barrett this resistance corresponds to a carbon content of 0.6 per cent. As carbon is probably absorbed from CO according to the reversible reaction

$$Fe + CO \rightleftarrows FeO + C$$

it seems natural to assume that not only carbon but also FeO is absorbed by the iron. In that case the result would be an alloy of ferrite, cementite (Fe_3C) and iron oxide (Fe O). For a carbon content of 0.1 per cent the alloy would contain 1.5 per cent cementite, and 0.59 per cent FeO. While cementite is slightly ferromagnetic, as shown by Hadfield and Hopkinson, FeO is paramagnetic, and a very poor conductor of electricity. With these two substances interspersed among the ferrite crystals, the low permeability and high resistance can be satisfactorily explained. From a further study of Table I it is seen that the Swedish charcoal iron has lost nearly all of its carbon by being melted in vacuo, the carbon content in the final iron being only 0.008 per cent. At the same time, as would be expected, its electrical resistance has been slightly lowered and its magnetic permeability considerably increased. Similarly, the three iron-carbon alloys melted in vacuo, 3C01, 3C02 and 3C03, have lost the larger part of the carbon added to them. While the additions amounted to 0.05, 0.10 and 0.50 per cent respectively, the chemical analysis of the final rods shows a carbon content of 0.013, 0.012 and 0.181 per cent. If to the former figures be added the carbon content of the electrolytic iron as deposited, namely 0.006 per cent, the loss of carbon is found to be 76.8, 80.5 and 64.4 per cent respectively. The corresponding loss for the Swedish iron was 95 per cent. The Bureau of Standards has demonstrated that such a loss occurs by melting electrolytic iron in vacuo, the loss

found being in one case 67 per cent, in another case 87.5 per cent. In the present case the electrolytic iron melted in vacuo not only did not lose any carbon, but actually gained a slight amount. In order to explain this apparent discrepancy it should be mentioned that the pressure used by the Bureau of Standards investigators in their vacuum furnace was 0.01 mm. of mercury, while the pressure used by the writer was from 2 to 5 mm. Based upon the facts above enumerated, the following explanation is now offered. Any oxygen left in the furnace combines with the carbon of the heating element and forms carbon monoxide (CO). This gas, as already stated in connection with the results obtained with the resistance furnace, reacts with the iron according to the reversible equation

$$Fe + CO \rightleftarrows FeO + C$$

until equilibrium is established. If now the pressure in the furnace be lowered the reaction will take place from right to left; that is, any FeO that may be present will be reduced by the carbon in the iron, with the result that the carbon content will be reduced until equilibrium is restored. Conversely, with an increase of pressure due to an admission of oxygen, the reaction will take place from left to right, and the carbon content, as well as the FeO, of the iron will be increased. Upon this hypothesis the difference between the carbon content obtained by the Bureau of Standards and that obtained by the writer is immediately explained.

The changes in the structure of the Swedish iron are very well illustrated by the photomicrographs shown in Figs. 33A and 33B and Fig. 34. Fig. 33A shows the non-homogeneous Swedish iron as rolled. The dark spots are probably partly slag and partly pearlite, shown to a higher magnification in Fig. 33B. Fig. 34 shows the iron after being melted in vacuo, being perfectly homogeneous and without any sign of pearlite. Figs. 30 to 32 show the structure for the iron-carbon alloys 3C01, 3C02 and 3C03, verifying in general the chemical analysis as to carbon content. By referring to Fig. 11 and Table I, it is seen that the electrical resistance and magnetic permeability for these iron-carbon alloys are not strictly in accordance with the chemical analysis. From the latter, 3C01 and 3C02 are approximately alike, while the electrical and magnetic tests indicate that 3C02 should have a higher carbon content than 3C01. Why this discrepancy should

exist is difficult to explain, as the analysis for 3C02 was repeated four times, giving results that agreed quite closely.

The effect of annealing at different temperatures is shown graphically in Fig. 8. From this figure it is seen that the permeability increases quite uniformly as the annealing temperature is raised, at first slowly, and then very rapidly as the annealing temperatures are raised from 700 to 800 deg. cent. Above 900 deg. cent. some uncertainty appears. The permeability is decreased for 950 deg. and again increased for 1000 deg. cent. Whether this result is due to mechanical strain in clamping the rod in the permeameter or whether it is due to different rates of cooling or to some other cause, the writer is not prepared to say. From the experience previously related it seems most probable that the drop for 950 deg. is due to mechanical straining, as it occurs for low values of H only. The experiments of Terry show that 1100 deg. cent. is the most favorable annealing temperature for pure iron. While the results shown in Fig. 8 are not conclusive in themselves, they help to confirm the results obtained by Terry. Another interesting point is shown in Fig. 8. For values of $H = 8$, or above, the permeability is decreased by annealing at temperatures above 900 deg. cent., and does not return to the higher value by further annealing at lower temperatures. Furthermore, upon annealing successively at decreasingly lower temperatures, the permeability is increased for low values of H. Such a process is, of course, equivalent to annealing at the highest temperature and cooling at a slower rate than was used for each of the successive annealings. This assumption was verified by annealing at 900 deg. cent. and cooling, first in 24 hours according to a logarithmic time-temperature curve, and finally in 48 hours according to a straight line connecting 900 and 200 deg. cent. These treatments increased the permeability considerably for low values of H, but did not alter it for high values of H. Quenching from 1000 deg. cent. in iced brine produced a decidedly magnetic hardening, but this hardening was again removed by reheating to 900 deg. cent. and slow cooling.

The results obtained with rod No. 3-39 are confirmed by those obtained with the three groups of rods made from electrolytic iron melted in vacuo. Thus, the rods of group 2, including Nos. 3-34, 3-36, 3-37 and 3-38, that were reheated to forging temperature, between 1000 and 1100 deg. cent., give a decidedly lower permeability for high values of H than rods that have not been heated above 900 deg. cent. The same is shown by the results

obtained for the rods of group 4, including Nos. 3-48, 3-49 and 3-50, after these rods had been annealed at 1080 deg. cent. Whether annealing at temperatures above 900 deg. cent. improves the permeability for low values of H has not been definitely demonstrated by this investigation. As was mentioned above, Terry has shown that 1100 deg. cent. is the most favorable annealing temperature for electrolytic iron as deposited, as this gave a lower hysteresis loss than annealing at lower temperatures. To be sure, the rods belonging to group 2, as well as rod No. 3-39, that some time during the process were heated above 1000 deg. cent., include the best rods magnetically of the entire series.[7] But the rods of group 4 were not improved materially by annealing at 1080 deg. cent. after having previously been annealed at 900 deg. cent.

The average magnetization curve for electrolytic iron melted in vacuo, as shown in Figs. 11 and 12, is based upon the results obtained after the final heat treatment, whether this gave the best results for each particular rod or not. This average also includes the results for rod No. 3-37, that perhaps should have been thrown out. The average curve is, therefore, somewhat lower than might be expected for 15 rods treated under more favorable conditions. However, it serves to indicate the place occupied by electrolytic vacuum iron, in relation to other grades of iron.

While the curve for the electrolytic vacuum iron is the highest of those represented in Fig. 12, the curve for the Swedish charcoal iron remelted in vacuo is a close second, and these two are far above the curves for commercial iron used at present for magnetic purposes. The maximum permeability for the average magnetization curve, as shown by Table I, is 12,950, occurring at a flux density of 6550 gausses. The maximum obtained, however, is 19,000 for rod No. 3-38, at a flux density of 9500 gausses.

Terry gives 11,000 as the maximum permeability obtained for electrolytic iron as deposited, but it is not perfectly clear whether this permeability occurred at ordinary temperatures or in the neighborhood of 760 deg. cent., as he compares this maximum value obtained with that obtained by Morris (15,000) and that obtained by Wells (17,000), both of which occurred at very low

7. Rod No. 3-37 has an exceptionally low permeability but this rod had probably had an accident sometime, as the chemical analysis shows that it contains 0.045 per cent carbon.

flux densities and near the critical temperature, 785 deg. cent. However, it is believed that Terry's maximum occurred at room temperature after annealing at 1100 deg. cent.

While high permeability is of interest for certain purposes, the characteristics of iron that are of special interest to the manufacturer and user of electrical machinery are hysteresis and eddy current losses, the latter depending largely upon the electrical resistance of the iron.

From Table I the hysteresis loss for B_{max} = 10,000 is seen to be less than one-half as high for the average electrolytic vacuum iron as it is for the commercial silicon steel, while for B_{max} = 15,000, the corresponding figure is about two-thirds. The reason why the hysteresis loss for the vacuum iron is not even still lower, compared with commercial iron, is readily seen by looking at the figures for retentivity. (See also Fig. 10). While the retentivity for B_{max} = 15,000 is 9940 for the average electrolytic vacuum iron, it is only 5400 for silicon steel. The hysteresis loss for Hadfield's best magnetic steels, the 2½ per cent silicon alloy and the 2¼ per cent aluminum alloy, as reported by Barrett, Brown and Hadfield, for B_{max} = 9000 is 1550 and 1440 ergs, respectively, per cu. cm. per cycle. Comparing these results, it is seen that in spite of the high retentivity, the hysteresis loss for the electrolytic vacuum iron is much lower than for any material thus far produced, of which the literature gives information. This is due to the low coercive force, namely, 0.34 gilbert per cm., this being the average value for the 15 rods.

The electrical resistance for the average vacuum iron is 9.96 microhms per cm. cube. The resistance for the standard transformer steel is 11.09 microhms, while that for the silicon steel is 51.15 microhms. Thus the eddy current losses per unit volume, for the same thickness of sheet and for the same maximum flux density, would be much in favor of the silicon steel. However, it is definitely known that the resistance of the latter can be raised by the addition of silicon or aluminum. What the effect of such additions upon the magnetic quality of the iron will be, remains to be seen, but judging from the effect they have upon commercial grades of iron, it seems probable that it will not be harmful.

While the photomicrographs are of interest primarily as showing the structure of electrolytic vacuum iron in general, and in what respects it differs from other grades of iron, certain conclusions as to the relation between the microstructure and

the magnetic quality of the iron may be drawn. Considering the series for rod No. 3-39, it appears that there is no general growth in the size of crystals. Annealing above 900 deg. cent., with subsequent slow cooling, breaks the crystals up into smaller parts. Quenching from 1000 deg. cent., this fine structure again gives way for larger crystals with indefinite boundaries, but the fine structure reappears upon subsequent annealing and slow cooling. The structure that seems to give the best magnetic quality is that shown in Figs. 19 and 21 for rod No. 3-39. This same structure is obtained for the best rod of the series, No. 3-38, as shown in Fig. 25, and for No. 3-31, in Fig. 23. The results of the critical temperature determinations show that the point Ar_3 (see Fig. 37) for the average electrolytic vacuum iron is 894 deg. cent., agreeing with the value found by the Bureau of Standards for pure iron.

Table II shows that magnetic and mechanical hardness go together, and serves to confirm further the results obtained by previous writers. It emphasizes the extreme mechanical softness of the electrolytic iron melted in vacuo, particularly after annealing at 900 deg. cent. In comparing Nos. 3C01, 3C02 and 3C03 with the rest of the rods, it should be remembered that the actual carbon content of these rods is 0.013, 0.012 and 0.181 per cent, respectively.

Summary and Conclusion

The results recorded in the previous pages may be summarized as follows:

1. Pure iron melted in an atmosphere of carbon monoxide, under atmospheric pressure, will absorb both carbon and oxygen, with the result that the iron thus produced is of an inferior magnetic quality.

2. Low-carbon iron melted in vacuo will lose 50 to 90 per cent of its original carbon content.

3. The magnetic quality of electrolytic iron melted in vacuo is decidedly superior to any grade of iron thus far produced, the maximum permeability obtained being 19,000 at a flux density of 9500 gausses. The average hysteresis loss obtained is less than 50 per cent of that found in the best grades of commercial transformer iron.

4. The specific electrical resistance of pure iron melted in vacuo is 9.96 microhms.

5. Swedish charcoal iron melted in vacuo has a magnetic

quality approximating that of electrolytic iron melted in vacuo, chiefly due to the reduction of the carbon content.

From these facts it appears that a superior quality of iron for magnetic purposes may be obtained by melting electrolytic iron in vacuo. While the electrical resistance of the iron thus obtained is very low, this defect may be remedied by the addition of such alloying elements as silicon or aluminum, elements that are known to increase the electrical resistance very materially without affecting the magnetic quality to any large extent. Experiments are now under way for determining the effect of such alloying elements, and the results will be published at some later date.

Whether iron melted in vacuo will ever become a commercial product depends, of course, upon whether any apparatus can be devised for producing such iron on a commercial scale at a cost that will not be prohibitive.

In conclusion, the writer wishes to acknowledge his indebtedness to a large number of persons connected with various departments of the University of Illinois, who have rendered valuable assistance in carrying on this investigation.

A number of large manufacturing companies have also shown their willingness to cooperate in the work, by going to great trouble and expense in preparing rods from commercial grades of iron.

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SOLENOIDS

BY CHARLES R. UNDERHILL

ABSTRACT OF PAPER

Maxwell's law for the attraction between the halves of a bar electromagnet is not correct for electromagnets of the plunger type with air gaps between the cores because the flux in the cores is, to a large extent, independent of the reluctance in the air gap on account of the magnetic leakage from the inner end of either core back to the other end of the same core.

In this paper, only the characteristics of direct-current electromagnets are discussed. An attempt is made to show the correct law of attraction for tractive electromagnets and to calculate the value of the magnetizing force at any point along the axis of any solenoid. Test characteristics are given to support the theories.

The work done by an electromagnet of the plunger type in closing its air gap is largely proportional to the length of the air gap, although, when the reluctance of the air gap and the total m.m.f. are of low value, the law of Carichoff is approximately correct for the total attraction.

THE EXTENSIVE use of electromagnets of the plunger type has caused the details of their design to become increasingly important. They are frequently divided into two classes; viz. long-range and short range. The equations in common use for calculating the static pulls due to short-range electromagnets, while more or less satisfactory for relatively short air-gaps, since the pulls are usually greater than calculated, are not applicable for predetermining the pulls when the air gaps are relatively long. In this paper, the static pull is always meant.

A general equation is desirable, by means of which the pulls may be predetermined for any type of movable-core electromagnet, whether or not it is provided with either a frame or stop, or both. Such an equation would be applicable to electromagnets designed to operate on either alternating or direct currents, after the mean effective values of the m. m. fs. which produce the pull had been determined at points throughout the range of travel of the plunger. The shapes of the mean effective pull curves for alternating-current electromagnets would naturally differ from those for direct current, owing to the different values of the m.m.fs. at corresponding points throughout the range of

travel, but the general law for the mean effective pull for a given m.m.f. would be the same in both cases, after making corrections for iron losses.*

In this paper, only the characteristics of direct-current electromagnets are discussed. The voltage across the windings and the current strength are assumed to be at constant value, in any given case, and the plungers are assumed to be at rest; so that it is not necessary to consider the effects of self-induction which are in evidence in alternating-current electromagnets and also in those operating on direct current when the plunger is in motion.

The fundamental equation of Maxwell,

$$P_s = \frac{B^2}{8\pi} \tag{1}$$

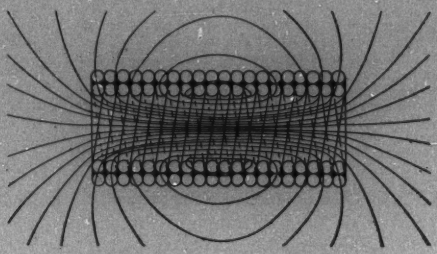


FIG 2—MAGNETIC FIELD OF SOLENOID

for the attraction in dynes per sq. cm., does not apply, either directly or tacitly, to the case of a solenoid-and-plunger only, or to plunger electromagnets with relatively long air gaps.

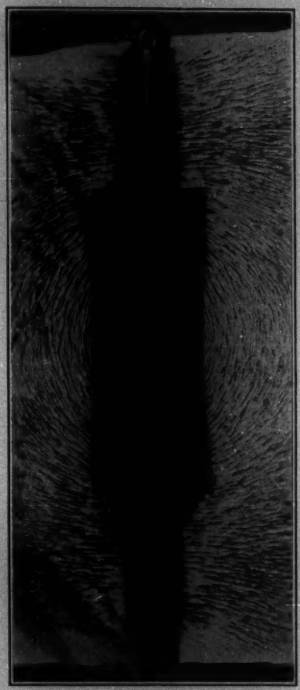
The familar analysis of Maxwell's equation is here given. The magnetic induction B consists of two components, $4\pi I$ (I being the intensity of magnetization in the iron) and the magnetizing force H. Hence

$$B = 4\pi I + H \tag{2}$$

Substituting (2) in (1),

$$P_s = 2\pi I^2 + IH + \frac{H^2}{8\pi} \tag{3}$$

*See "Alternating-Current Electromagnets," *Electrical World*, Vol. 63, No. 5, p. 260 (1914).



[UNDERHILL]

FIG. 1—MAGNETIC FIELD OF BAR ELECTROMAGNET WITHOUT INTERNAL AIR-GAP

[UNDERHILL

FIG. 5—MAGNETIC FIELDS WHEN AIR-GAP IS INTRODUCED

which is the equation for the attraction in dynes per sq. cm. between the two halves of a bar electromagnet separated at its middle at right angles to the axis of the core, but perfectly joined magnetically; hence there is assumed to be no leakage from the

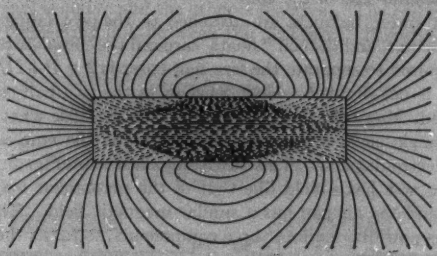


FIG. 3—FIELD OF BAR PERMANENT MAGNET

ends of the abutting half-cores back to the opposite end of the same half-core, as shown in Fig. 1.

Conventionally stated, the attraction between the ends of the iron half-cores is $2\pi I^2$; IH is the attaction between the half-coil

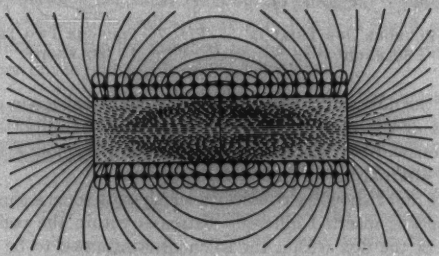


FIG. 4—BAR ELECTROMAGNET WITH DIVIDED CORE

and half-cores, and $\frac{H^2}{8\pi}$ is the attraction between the half-coils, which is not available in a single coil as commonly used in practise and is, therefore, neglected.

In Figs. 2 and 3 are shown the fields of a solenoid and a bar permanent magnet respectively. The following assumptions apply to Fig. 4, which shows the field of a practical bar electro-

magnet: The core is cut across at the middle but the joint is as perfect magnetically as though the structure were solid; the coil is uniformly wound in layers; the complete core fits closely inside of the coil, but either half can be moved, without friction, along the horizontal axis of the coil.

When spring balances are attached to the protruding ends of the half-cores, and the coil "floats" around the complete core, the pull required to separate the two half-cores is $2\pi I^2+IH$, since the coil is not divided. Now, as soon as the two half-cores are separated, Maxwell's law no longer holds, because what before was a single electromagnet has now become the equivalent of three electromagnets. This is clearly shown in Fig. 5. Each half-core now has a field like that of the permanent magnet in Fig. 3, and the air gap has a similar magnetic field. The total m.m.f. is now divided into three components, so far as the conditions inside of the core of the coil are concerned, and this is the

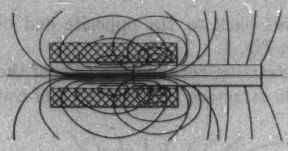


FIG. 6—PLUNGER ONE-THIRD IN SOLENOID

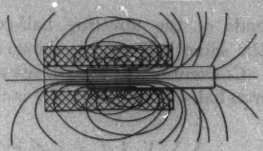


FIG. 7—PLUNGER TWO-THIRDS IN SOLENOID

basis of the doctrine of the effects of magnetic leakage in electromagnets of the plunger type, which is of great importance in continuous-current electromagnets but of paramount importance in alternating-current electromagnets.

Figs. 6 and 7 show the conditions which exist when a single core or plunger is inserted different distances within the coil. The density of the flux within the solenoid is assumed to be always the same at a given point, and is greatest at the middle of the coil along the horizontal axis. The position of maximum structural flux density of the plunger is always, approximately at least, half way between the inserted end of the plunger and the end of the coil at which the plunger enters. This is apparent in Fig. 5. When the middle of the plunger is at the middle of the coil, the two magnetic fields coincide and force is required to move the plunger in either direction.

When two plungers are placed within the solenoid, as in Figs.

5 and 8, spring balances are attached to the protruding ends, and the balances moved in the direction of the arrows, with the coil "floating" on the plungers, the pull as measured on either balance is the total pull which can be obtained with either plunger, since one pull is active and the other is reactive. The coil merely acts as a connecting link between the plungers. There is, how-

FIG. 8—SOLENOID WITH TWO PLUNGERS

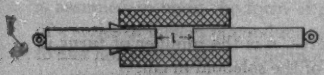


FIG. 9—SOLENOID WITH ONE PLUNGER FIXED IN POSITION

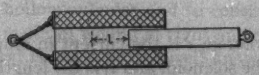


FIG. 10—ONE OF THE PLUNGERS IS OMITTED

ever, some attraction between the ends of the plungers, but this is slight when the air gap is so long. Therefore, omitting the attraction between the inner ends of the plungers, it makes no difference whether the conditions are as in Fig. 8; in Fig. 9, wherein one plunger is rigidly fastened to the coil, or as in Fig. 10, wherein one of the plungers is omitted entirely.

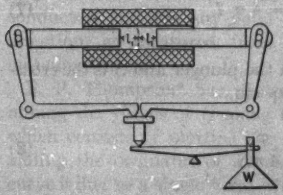


FIG. 11—BOTH PLUNGERS WORKING TOGETHER

In any case, the attraction that draws the plunger within the coil is the product of the average intensity of magnetization within the structure of the plunger and the average magnetizing force within the solenoid. This is found true by actual test and can be proved on the principle of work by assuming the pull to be constant throughout the range or distance of travel of the plunger. In Fig. 8, either plunger, when acting separately, can do $p\,l$ units of work, wherein p is the pull. The same holds true for the conditions in Figs. 9 and 10. When both plungers act together, the work done is $2\,p\,l_1$, as illustrated in Figs. 8 and 11, but the work done in both cases is the same. In Fig. 11, the two plungers can

lift the weight W equal to $2p$, but only through a distance l_1, which is equal to $\frac{l}{2}$. Hence the attraction or pull between a solenoid and plunger is

$$P_s = I H \tag{4}$$

The magnetizing force at the center of a solenoid whose length is great as compared with its average radius is

$$H = \frac{0.4\,\pi\,i\,n}{L} \tag{5}$$

wherein i is the current in amperes, n is the number of turns in the solenoid, and L is the length of the solenoid in cm.

The magnetizing force at any point on the horizontal axis of any uniformly wound solenoid is

$$H = \frac{0.2\,\pi\,i\,n\,h}{L} \tag{6}$$

wherein h is the coefficient of magnetizing force which is proportional to the length and average radius of the solenoid.

Let

$$\frac{\phi_i}{S} = 4\,\pi\,I \tag{7}$$

wherein ϕ_i is the structual flux in the plunger and S is the cross-sectional area of the plunger in sq. cm.

Then

$$I = \frac{\phi_i}{4\,\pi S} \tag{8}$$

Substituting (6) and (8) in (4),

$$P_s = \frac{\phi_i\,i\,n\,h}{20\,S\,L} \tag{9}$$

The pull in dynes is

$$P_d = P_s\,S \tag{10}$$

Substituting (10) in (9),

$$P_d = \frac{\phi_i\, i\, n\, h}{20\ L} \tag{11}$$

The attraction in kg. is

$$P = \frac{\phi_i\, i\, n\, h}{20 \times 981{,}000\ L} = \frac{\phi_i\, i\, n\, h}{19{,}620{,}000\ L} \tag{12}$$

The *approximate* values of the coefficient of magnetizing force h are found in the manner described below. The solenoid is assumed to be in the form of a hollow cylinder and to consist of a series of helices of conducting material wound at right angles to the horizontal axis. The method is based on the well-known equation for the magnetizing force H due to a single turn of the conductor in which current is flowing, as measured along the horizontal axis of the turn.

The expression is

$$H = \frac{0.2\ \pi\ i\ r^2}{(r^2 + x^2)^{\frac{3}{2}}} \tag{13}$$

wherein r is the average radius of the conductor as measured from the horizontal axis to the center of the cross-section of the conductor, and x is any point on the horizontal axis in either direction, as measured from the vertical axis; r and x are measured in cm.

S. P. Thompson* has shown a graphical method for determining the values of H along the horizontal axis of a solenoid, which consists of plotting the H curve for each turn and then adding the ordinates of all of the curves together. The first curve is due to a single turn, while the adjacent curve represents the magnetizing force due to a second turn, one centimeter from the first, plus that due to the first turn. This general idea is carried out throughout the rest of the figure. Both sides of each curve are exactly similar. Taking the maximum value of H for a single turn as unity, the maximum value of H at the middle of a solenoid consisting of an infinite number of turns would be two.

For the purpose of this paper, the values of h have been cal-

*"The Electromagnet," p. 248.

culated for certain points, and curves drawn through these points from which any value of H may be found. The method consists of dividing the length L of a solenoid by its average radius r and designating the quotient, or the number of sections, by m; each section being considered in the same manner as each single turn in the method described above.

Then

$$m = \frac{L}{r} \tag{14}$$

The magnetizing force at the center of any one section without any other section near it is

$$H_c = \frac{0.2\,\pi\,i\,n_s}{r} \tag{15}$$

wherein n_s is the number of turns in one section.

At any distance x, as measured in section-lengths on the horizontal axis from the center of the section,

$$H_c = 0.2\,\pi\,i\,n_s\,\frac{r^2}{(r^2 + x^2)^{\frac{3}{2}}} \tag{16}$$

Let

$$q = \frac{r^2}{(r^2 + x^2)^{\frac{3}{2}}} = \frac{H_c}{0.2\,\pi\,i\,n_s} \tag{17}$$

and

$$h_a = q\,r \tag{18}$$

Then at any distance x on the horizontal axis, from the center of the section,

$$h_a = \frac{r^3}{(r^2 + x^2)^{\frac{3}{2}}} \tag{19}$$

while at the center of the section, $h_a = 1$

But

$$x = r\,m_s \tag{20}$$

wherein m_s is the distance in section-lengths from the center of the section.

Therefore

$$h_a = (1 + m_s^2)^{-\frac{3}{2}} \tag{21}$$

Let a represent the section of reference, m_r the number of sections to the right of a, and m_l the number of sections to the left of a. (See Fig. 12).

Then

$$h = \sum_{1}^{m_r} h_a + \sum_{1}^{m_l} h_a + 1 \tag{22}$$

That is, h represents the sum of all of the values of $\frac{H_c r}{0.2 \pi i n_s}$ at the center of the section of reference.

The equation for h at the center of either end-section may also be expressed

$$h = \sum_{1}^{m-1} h_a + 1 \tag{23}$$

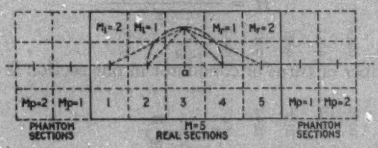


FIG. 12

For points outside of the solenoid, on the horizontal axis, at the center of any "phantom" section,

$$h = \sum_{m_p}^{m+m_p-1} h_a \tag{24}$$

wherein m_p is the number of the phantom section.

Likewise the value of h at points midway between the centers of the sections may be found by an equation

$$h = \sum_{.5}^{m_r-.5} h_a + \sum_{.5}^{m_l-.5} h_a \tag{25}$$

wherein m_r and m_l are the number of whole sections to the right or left, respectively, from the chosen points of reference.

The equation for the phantom sections, or those points outside of the solenoid, is

$$h = \sum_{m_p-.5}^{m+m_p-.5} h_a \tag{26}$$

Substituting (17) and (18),

$$h_a = \frac{H_c r}{0.2 \pi i n} \tag{27}$$

By definition

$$h = \Sigma h_a \tag{28}$$

Therefore

$$h = \frac{H r}{0.2 \pi i n_s} \tag{29}$$

whence

$$H = \frac{0.2 \pi i n_s h}{r} \tag{30}$$

The number of turns of conductor in one section is

$$n_s = \frac{n}{m} \tag{31}$$

wherein n is the total number of turns in the solenoid and m is the number of sections.

Substituting (14) and (31) in (30),

$$H = \frac{0.2 \pi i n h}{L} \tag{6}$$

When h reaches its maximum value of 2, as in a solenoid whose length is great as compared with its average radius, the magnetizing force at the center is

$$H = \frac{0.4 \pi i n}{L} \tag{5}$$

In Table I, the column marked m_s represents the number of sections from the section of reference a as measured in either direction. The section of reference is not counted. The column h_a indicates the values corresponding to m_s as calculated by equation (21), while in the column marked $\sum_1^{m_s} h_a$ are given the sums of h_a corresponding to the values of m_s. The value of h_a for the section of reference is one. It is seen that the series of h_a converges rapidly.

TABLE I. Values of k.

m_s	k_a	$\sum_1^{m_s} k_a$	$\sum_2^{m_s} k_a$	$\sum_3^{m_s} k_a$	$\sum_4^{m_s} k_a$	$\sum_5^{m_s} k_a$	$\sum_6^{m_s} k_a$	$\sum_7^{m_s} k_a$	$\sum_8^{m_s} k_a$	$\sum_9^{m_s} k_a$	$\sum_{10}^{m_s} k_a$	$\sum_{11}^{m_s} k_a$
1	.354	.354										
2	.089	.443	.089									
3	.0316	.475	.121	.032								
4	.0143	.489	.135	.046	.014							
5	.00754	.496	.143	.053	.022	.0075						
6	.00444	.501	.147	.058	.026	.012	.0044					
7	.00283	.504	.150	.061	.029	.015	.0073	.0028				
8	.00191	.506	.152	.063	.031	.017	.0092	.0047	.0019			
9	.00135	.507	.153	.064	.032	.018	.0105	.0061	.0033	.0014		
10	.000985	.508	.154	.065	.033	.019	.0115	.0071	.0042	.0023	.00098	
11	.000742	.509	.155	.066	.034	.020	.0123	.0078	.0050	.0031	.00173	.00074
12	.000573	.509	.156	.066	.035	.020	.0128	.0084	.0056	.0036	.00230	00132

In Table II, which shows the values of h, m is the total number of sections in the solenoid and a is the number of the section of reference as counted from either end of the solenoid; 1 is an end-section; 2, 3, 4, 5 and 6 are middle sections when m is 3, 5, 7, 9 and 11 respectively.

TABLE II. Values of h.

Sec. of Ref. a / m	1	2	3	4	5	6
1	1.000					
2	1.354					
3	1.443	1.707				
4	1.475	1.797				
5	1.489	1.828	1.886			
6	1.496	1.842	1.918			
7	1.501	1.850	1.932	1.949		
8	1.504	1.854	1.939	1.964		
9	1.506	1.857	1.944	1.971	1.978	
10	1.507	1.859	1.947	1.976	1.985	
11	1.508	1.861	1.949	1.978	1.990	1.993

With 11 sections, the limit two at the center of the solenoid is approximated. If any solenoid be bent into the form of a ring, h will have a value of two at any point along what was formerly its horizontal axis.

Table III is similar to Table I but shows the values of h for points midway between the centers of the sections. Fig. 13 shows the method of finding the values of h at other points between the centers of the sections. In this figure, $m = 3$.

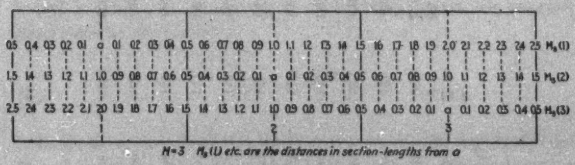


FIG. 13

The curves marked h in Figs. 14 to 24 inclusive have been prepared from the above equations and tables. The peaks of the h curves in Figs. 16 and 17 are slightly irregular owing to the use of points calculated for the half-sections. In Figs. 18 to 24 inclusive, only points for whole sections were used for the peaks.

TABLE III.

Values of k.

$m_s-.5$	k_a	$\sum_{.5}^{m_s-.5} k_a$	$\sum_{1.5}^{m_s-.5} k_a$	$\sum_{2.5}^{m_s-.5} k_a$	$\sum_{3.5}^{m_s-.5} k_a$	$\sum_{4.5}^{m_s-.5} k_a$	$\sum_{5.5}^{m_s-.5} k_a$	$\sum_{6.5}^{m_s-.5} k_a$	$\sum_{7.5}^{m_s-.5} k_a$	$\sum_{8.5}^{m_s-.5} k_a$	$\sum_{9.5}^{m_s-.5} k_a$	$\sum_{10.5}^{m_s-.5} k_a$
0.5	.716	.716										
1.5	.171	.886	.171									
2.5	.0512	.937	.222	.0512								
3.5	.0207	.958	.243	.072	.021							
4.5	.0102	.968	.253	.082	.031	.010						
5.5	.0057	.974	.259	.088	.037	.016	.0057					
6.5	.0035	.978	.262	.091	.040	.019	.0092	.0035				
7.5	.0023	.980	.264	.094	.042	.022	.0115	.0058	.0023			
8.5	.0016	.982	.266	.095	.044	.023	.0131	.0074	.0039	.0016		
9.5	.0011	.983	.267	.096	.045	.025	.014	.0086	.0051	.0027	.0011	
10.5	.00085	.984	.268	.097	.046	.025	.015	.0094	.0059	.0036	.0020	.00085
11.5	.00065	.984	.269	.098	.047	.026	.016	.0101	.0066	.0042	.0026	.00150

TABLE IV

m_s	h_a	m_s	h_a
0.	1.000	1.1	0.304
0.1	0.985	1.2	0.262
0.2	0.943	1.3	0.227
0.3	0.879	1.4	0.196
0.4	0.800	1.5	0.171
0.5	0.716	1.6	0.149
0.6	0.631	1.7	0.130
0.7	0.550	1.8	0.114
0.8	0.476	1.9	0.101
0.9	0.411	2.0	0.089
1.0	0.354		

The coefficient of m.m.f. for the plunger circuit is f_p. Its value is

$$f_p = \int_x^{l_p} h \, d \, l_p \tag{32}$$

wherein l_p is any distance along the horizontal axis of the solenoid (abscissas in the figures). In this paper it represents the point at which the inserted end of the plunger rests.

The l_p curves were obtained directly from the h curves by integrating with a planimeter from the extreme left-hand point of each curve.

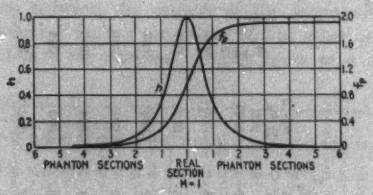


FIG. 14

In each of the above figures, the maximum value of f_p approaches the limit

$$f_{max} = 2\,m \tag{33}$$

wherein m is the number of sections in the solenoid. The total m.m.f. is, of course, equally divided on each side of the center of the solenoid.

A convenient method of analyzing the action of a solenoid and plunger is to think of the plunger as having been inserted

(from the left in the figures) for a given distance, say to the middle of the solenoid, and then conceiving the m.m.f. as consisting of two components, one of which produces the magnetizing force to magnetize the plunger while the other component produces the

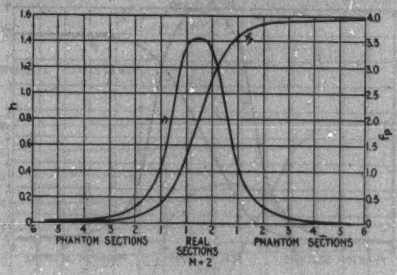


FIG. 15

magnetizing force to coact with the flux in the plunger and thus cause attraction.

The value f_p bears the same relation to the m.m.f., F_p, that h bears to the magnetizing force. Therefore,

$$F_p = 0.2\,\pi\, i\, n f_p \tag{34}$$

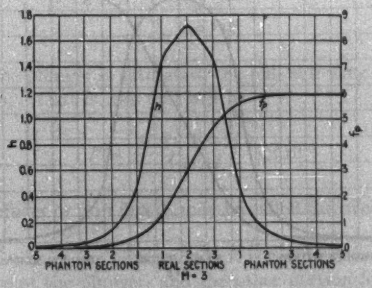


FIG. 16

Hence, at the middle of any solenoid, the m.m.f. available to magnetize the plunger is but one-half of the total, while, at other points along the horizontal axis of the solenoid, the values of f_p are to be read from the curves.

The magnetic circuit of the plunger may be considered as consisting of that portion of the plunger which is inserted into the solenoid and the surrounding air or non-magnetic region between the inserted end of the plunger and the end of the solenoid at

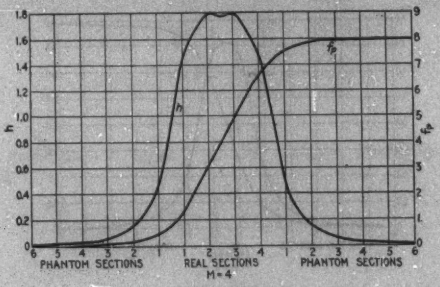


FIG. 17

which the plunger enters. Actually, the flux enters or leaves the protruding plunger over the entire area of that part of the plunger. Practically, it is convenient to assume that it enters the plunger between a point, equal to one-half of one section-length from the

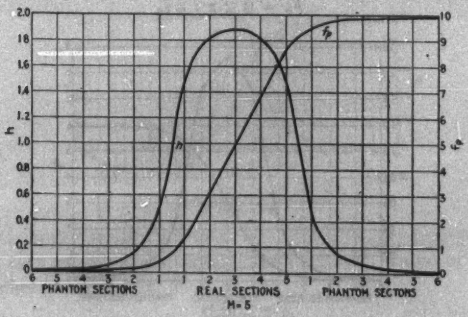


FIG. 18

end of the solenoid at which the plunger enters, and the middle of the plunger. This makes it possible to consider the point l_p as being at the center of the section of the same number as the point. Thus, at the center of the third section from, say, the left-hand end of the solenoid, $l_p = 3$.

As the plunger passes into the solenoid, the iron flux ϕ_i, which is equal to $S\,(B-H)$, increases, and the pull, for a constant value of H, will increase directly with ϕ_i until saturation is attained. Thereafter, the pull

$$P = \frac{\phi_i\, i\, n\, h}{1962\, L} \times 10^{-4} \tag{12}$$

will remain constant.

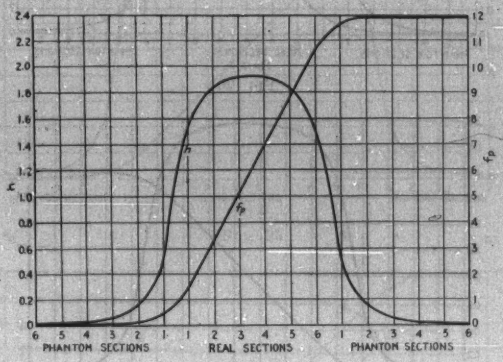


FIG. 19

After the plunger is saturated, the pull will vary directly with $H = i\,n\,h$. That is, the pull will be

$$P = \frac{H\,S\,(B-H)}{1962\,L} \times 10^{-4} \tag{35}$$

The plunger or iron flux ϕ_i may be called the average effective flux.

One portion of the plunger m.m.f. is required to overcome the reluctance of the plunger, and the other portion forces the flux through the air from the inserted end of the plunger to the end of the solenoid at which the plunger enters.

This leads to the problem of ascertaining the reluctance of the air-return circuit. The mean length of this portion of the plunger circuit is somewhere between 0 and ∞ while the cross-section is

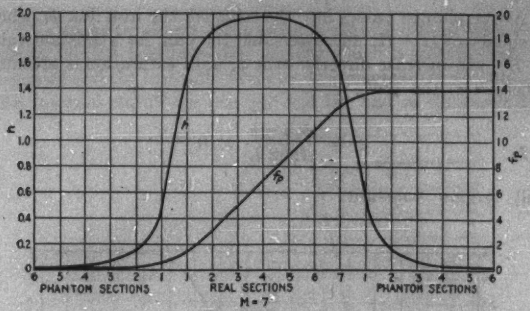


FIG 20

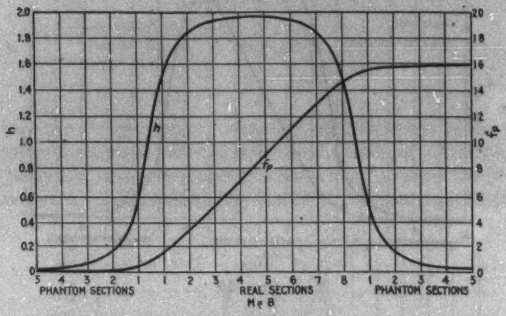


FIG. 21

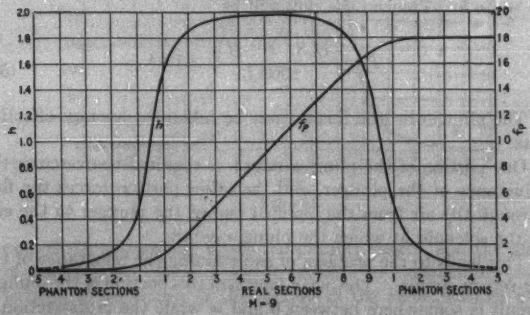


FIG. 22

infinite. It is difficult to obtain accurate experimental data owing to the fact that the plunger is not uniformly magnetized, but may be saturated at or near the middle of that portion within the solenoid, with lessening degrees of magnetization on either side of this point.

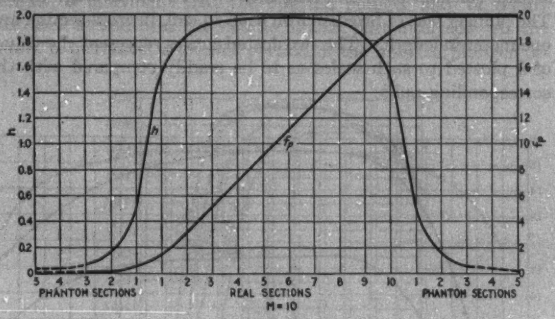


FIG. 23

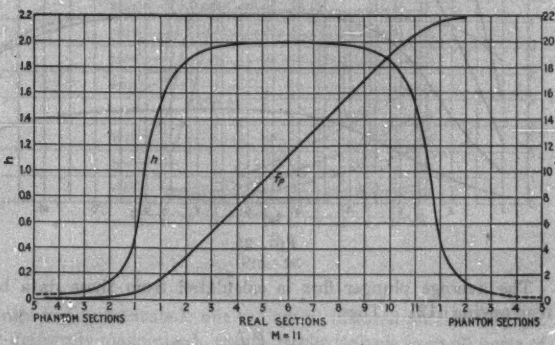


FIG. 24

The average reluctance of the air portion of the plunger circuit is the difference between the total average reluctance of the plunger circuit and the reluctance of the plunger.

$$R_a = \frac{F_p}{\phi_1} - \frac{l_p r}{S(\mu_1 - 1)} \tag{36}$$

wherein ϕ_i is the total flux in the plunger circuit, l_p is the length of the plunger, in section-lengths, inserted into the solenoid, S the cross-sectional area of the plunger in sq. cm., and μ_i the average permeability of the plunger.

In Fig. 25 are shown the test characteristics of an eleven-section solenoid 30.5 cm. long and of 2.76 cm. average radius. The plunger was of Swedish iron 6.45 sq. cm. in cross-section and one meter in length. The two dotted curves represent the values of h plotted to such scales as to be readily compared with the corresponding pulls.

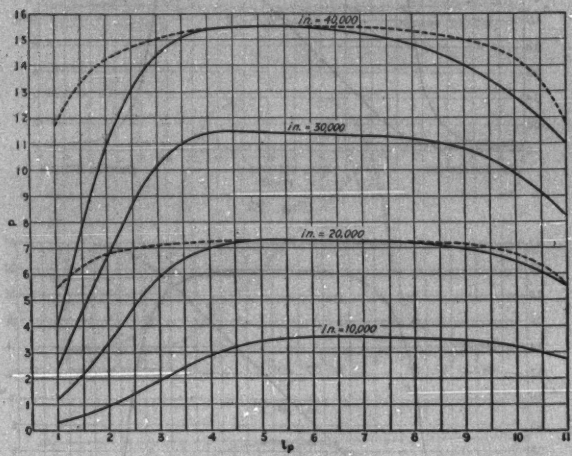


FIG. 25

The average plunger flux is calculated from these data by rearranging (12). Then

$$\phi_i = 1962 \frac{P\,L}{i\,n\,h} \times 10^4 \tag{37}$$

Fig. 26 shows the calculated values of $\frac{\phi_i}{S}$ plotted against points representing the centers of the sections of the solenoid. The calculated values of $\frac{F_p}{\phi_i}$ are also plotted in Fig. 26. The average

air reluctance can only be calculated from the test data below saturation. The slopes of the curves indicate that the total reluctance below saturation is less than 0.1 oersted.

The calculated flux-densities are, necessarily, only averages. Owing to the relatively low calculated reluctances with the lower m.m.fs., it is evident that the inserted plunger may be highly saturated at and near the middle of that part inserted. As the m.m.f. is increased, a greater portion of the inserted plunger be-

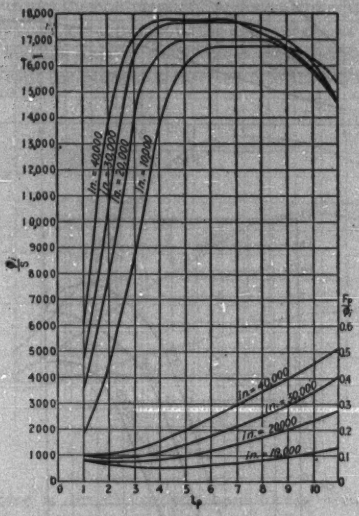


FIG. 26

comes highly saturated; but the entire inserted portion will not be uniformly magnetized, owing to the leakage from all parts of its surface.

Under these conditions, the average reluctance of the plunger might be in excess of that of the air-portion of the magnetic circuit. In the case of the eleven-section solenoid, the length of the coil was 30.5 cm. The cross-sectional area of the plunger was 6.45 sq. cm. The reluctance of that portion of the plunger inserted into the entire length of the solenoid would, therefore,

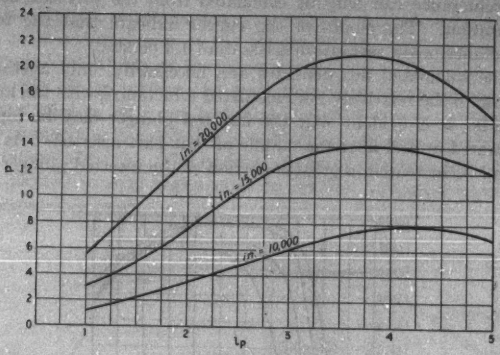

24
22
20
18
16
14
12
10
8
6
4
2
0
P
1
2
3
4
5
i_p
$in = 20,000$
$in = 15,000$
$in = 10,000$

FIG. 27

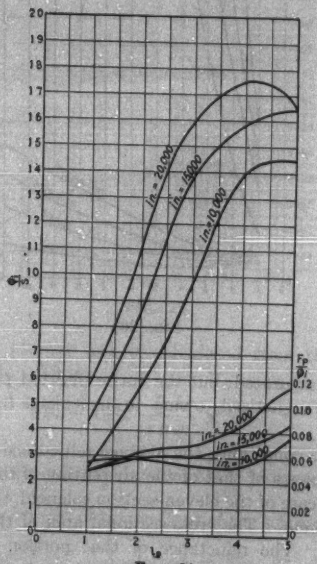

20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Φ_s
F_p
Φ_i
0.12
0.10
0.08
0.06
0.04
0.02
0
1
2
3
4
5
i_p
$in = 20,000$
$in = 15,000$
$in = 10,000$
$in = 20,000$
$in = 15,000$
$in = 20,000$

FIG. 28

be 4.73 oersteds with unit permeability. With an average permeability of 20, the average reluctance would be 0.237 oersted, exclusive of that of the air-return circuit.

Fig. 27 shows the results of a test of a five-section solenoid of 3.5 cm. average radius. The plunger was of cold-rolled steel 11.4 sq. cm. in cross-section and approximately 25 cm. long. The length of the solenoid was 17.8 cm. Fig. 28 shows the calculated flux-densities and reluctances. This figure shows lower total reluctances owing to the greater cross-section of the plunger.

The reluctance of the non-magnetic region surrounding a plunger must be nearly constant throughout the entire travel of the plunger because the leakage area of the plunger increases directly with the distance that the plunger is inserted into the solenoid. This

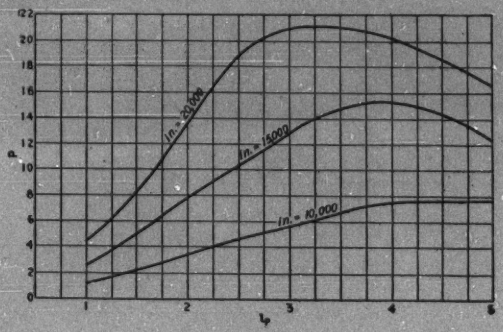


FIG. 29

leakage surface is directly proportional to the diameter of the plunger. The diameters of the plungers used in the tests of the eleven-section and five-section solenoids were 2.8 cm. and 3.8 cm. respectively. Hence, the ratio of the reluctance of the surrounding air-spaces should be as 1 to 0.74. Taking the air reluctance of the five-section solenoid as 0.06 oersted, that for the eleven section solenoid should be 0.081 oersted. The air reluctances are probably lower than assumed.

In Fig. 29 are shown the calculated characteristics of the five-section solenoid, the assumptions being that the total reluctance of the plunger circuit has a constant value of 0.06 oersted and that the limit of the average structural flux density is 17,000. The calculated flux densities are shown in Fig. 30.

Fig. 29 compares favorably with Fig. 27, excepting that the maximum pull due to 15,000 ampere-turns is in excess of the test data, and the maximum pull due to 20,000 ampere-turns occurs at a point somewhat to the left of the point observed in the test. This is largely due to the straight-line magnetization curve assumed as in Fig. 30. It is to be observed that the pulls at other points on the curves compare favorably with the test data, proving that the reluctance of the air-portion of the magnetic circuit must be low.

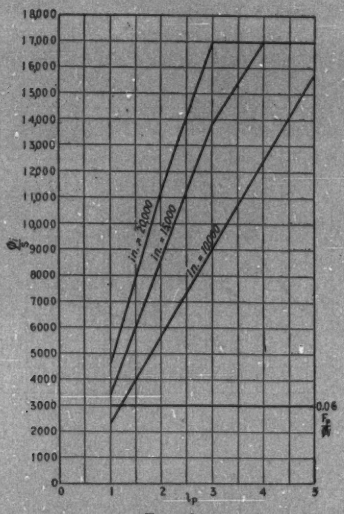


FIG. 30

Fig. 31 shows the calculated characteristics of the eleven-section solenoid. The assumptions are the same as those used in the calculation of the five-section solenoid, excepting that the assumed constant reluctance is 0.081 oersted. The calculated flux-densities are shown in Fig. 32.

The remarks regarding Fig. 29 apply to Fig. 31 also. The pulls do not become at a maximum at the same points as in the test curves and there is some variation in these pulls. The former is to be expected with a straight-line magnetization curve from

zero to saturation. The reluctances of the plungers vary with different degrees of magnetization and the saturation points of the plungers, as well as constant reluctances, are assumed. The test data indicate that the total reluctance varies with the m.m.f.

The effects of the apparent reaction which takes place as the magnetic center of the plunger approaches the magnetic center of the solenoid, are evident in Fig. 28. As is well known, all relative movement ceases when these two points coincide. In these tests, the plungers were considerably longer than the solenoids.

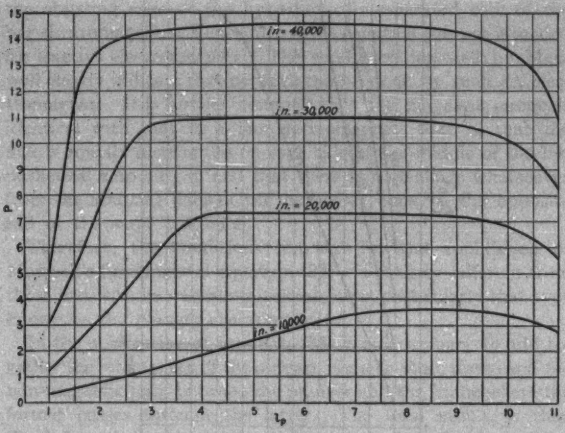


FIG. 31

Figs. 27 and 29 illustrate the action of a solenoid-and-plunger very nicely. When the flux density in the plunger is low, the maximum pull may occur at a point near the end of the solenoid opposite to that at which the plunger enters, whereas, with high flux-densities, the maximum pull may occur when the inserted end of the plunger is at the middle of the solenoid. The pull cannot be at a maximum at points between the middle of the solenoid and the end at which the plunger enters, although it may be nearly uniform for equal distances on both sides of the middle, in cases of long solenoids. In cases of very short solenoids

the maximum pull may occur at points outside of the solenoid at the end opposite to that at which the plunger enters.

Owing to the low reluctances of the plunger circuits of this type of electromagnet, the equation

$$P_d = \frac{\phi_t^2}{8\,\pi\,S} \tag{38}$$

cannot be applied to predetermine the pull due to plunger electromagnets, excepting for zero air gap. Equation (**38**) is not general,

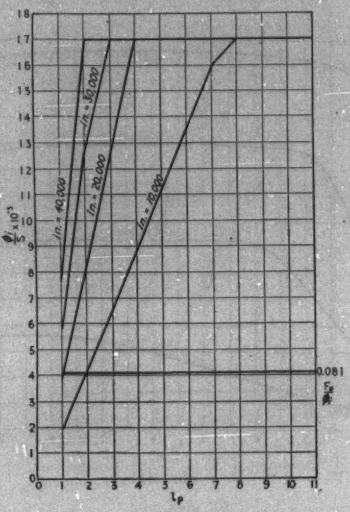


FIG. 32

but is for the attraction proportional to $(B - H)^2$ between the plunger and the stop only. On account of the leakage from the end of the inserted plunger back through the air and frame to the end of the solenoid at which the plunger enters, when there is an air gap, the flux densities in the plunger may be much greater than assumed, when the assumption is that nearly all of the flux passes through the air gap.

The magnetic circuit of an iron-clad stopped solenoid, or plunger electromagnet, consists of more than one path. The m.m.f.

forces flux through the air gap but it also forces another flux from the end of the plunger through the air and frame and back to the opposite end of the plunger. This latter flux produces a relatively strong pull whether any flux passes through the air gap, between the plunger and the stop, or not. There are, therefore, two separate and distinct actions to be considered, viz: the pull due to the flux density, $B - H$, in the air gap and the pull due to the flux in the plunger coacting with the magnetizing force due to the ampere turns in the solenoid.

One of the assumptions upon which Maxwell's fundamental equation is based, is that there is no air gap whatsoever between the abutting ends of the hypothetically-separated core of the bar electromagnet. Hence Maxwell's equation was not intended for tractive electromagnets. The conditions imposed by Maxwell clearly indicate that no work can be done by such an electromagnet. It is further assumed that the magnetic circuit is identical with that of a bar electromagnet; that is, that the flux is equally distributed on each side of the middle of the hypothetical zero air gap and that there is no leakage whatsoever from the abutting ends of the half-cores back to the opposite end of the same half-core.

Therefore, the conditions imposed for the application of Maxwell's fundamental equation (**38**) are entirely different from those met with in tractive electromagnets; particularly that type known as the plunger electromagnet.

In the application of equation (**38**) it is customary to add together the reluctances of the air gap, plunger, stop, frame and the non-magnetic joint between the plunger and the frame where the former passes through the latter. The total m.m.f. is then divided by the total reluctance and the resulting flux is assumed to be the total flux in the magnetic circuit, and to be the same in the air gap as in the plunger and stop. Allowance for leakage is seldom made because the pulls, with moderately long air gaps, are usually found to be in excess of those calculated. The total flux divided by the cross-sectional area of the plunger is called the magnetic induction B in the plunger and this value is also usually assumed for the flux-density in the air gap. When the reluctance of the air gap is equal to the sum of the reluctances of the rest of this single magnetic circuit, the maximum amount of work is assumed to be obtainable, when work is defined as initial pull $\times$ length of air gap.

The total pull, by Maxwell's equation (**3**), as modified by

neglecting the last term of the right-hand member (which is not available in a solid coil), is

$$P_s = 2\pi I^2 + I H \tag{39}$$

in dynes per sq. cm.

$$P_i = 2\pi I^2 \tag{40}$$

is the structural pull, in dynes per sq. cm., between the abutting ends only of the half-cores of the bar electromagnet.

Now when an air gap is introduced between the plunger and the stop, the intensity of magnetization in the iron does not decrease with the flux density (less H) in the air gap on account of the leakage from the inner end of the plunger, through the air or ether, back to the end at which the plunger enters the coil.

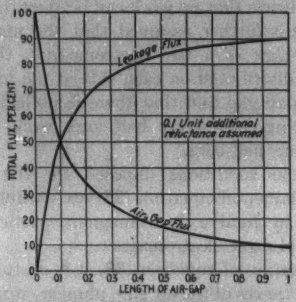


FIG. 33—RELATIVE VALUES OF FLUX

This leakage tends to sustain the intensity of magnetization in the plunger and to produce the "solenoid pull" when the flux density (less H) in the air gap is exceedingly low, or when there is no air gap (in the usual sense) as when only the plunger is inserted into the coil and there is no other magnetic material near.

Generally speaking*, the leakage pull is a maximum when the length of the air gap in a plunger electromagnet is maximum, but when the length of the air gap is reduced to zero, there can be no leakage (as mentioned above) whatsoever, and the law of the pull required to separate the plunger from the stop is then expressed by equation (**39**). On the other hand, the air gap

*See "Alternating-Current Electromagnets," *Electrical World*, Vol. 63, No. 5, p. 260 (1914).

flux will vary inversely with the length of the air gap so that the general conditions, so far as the air gap and leakage fluxes are concerned, are graphically represented in Fig. 33.

It will now be seen that Maxwell's law is true for a closed air gap, under the ideal conditions previously mentioned, but that it does not hold for tractive electromagnets unless modified to allow for the extra pull due to leakage. Therefore, the equation for the total pull due to a plunger electromagnet with an air gap and fixed stop may be constructed as follows: From (**7**), $\frac{\phi_i}{S} = 4\,\pi\,I$, wherein ϕ_i is the total structural flux in the iron. Let ϕ_g represent the flux in the air gap less that due to the magnetizing force, and allow P_g to represent the pull in dynes per sq. cm. in the air gap due to ϕ_g. Then

$$P_g = \frac{\phi_g^2}{8\,\pi\,S^2} \tag{41}$$

Expressed in dynes,

$$P_g = \frac{\phi_g^2}{8\,\pi\,S} \tag{42}$$

The pull in kilograms, under the above conditions, is

$$P_G = \frac{\phi_g^2}{8\,\pi \times 981{,}000\,S} = \frac{\phi_g^2}{247\,S} \times 10^{-4} \tag{43}$$

Adding equations (**43**) and (**12**), the total pull, in kilograms, for a plunger electromagnet, with or without an iron frame, or a stop, is

$$P = \left(\frac{\phi_g^2}{247\,S} + \frac{\phi_i\,i\,n\,h}{1962\,L}\right) \times 10^{-4} \tag{44}$$

which is the general pull equation for tractive electromagnets of the plunger type.

The flux in the stop also coacts with the magnetizing force in the coil which tends to produce motion, but the stop and coil are usually fixed in position so that no relative motion results. The leakage, from the inserted end of the stop back through the air and frame to the place where it is attached to the frame, tends to cause a greater total flux to pass through the stop than is usually calculated. This causes the reluctance of the stop to be greater than calculated, on the assumption that the flux in the plunger and stop is the same as that in the air-gap.

In Fig. 34* are shown the test characteristics of the eleven-section solenoid, 30.5 cm. long, surrounded by a massive wrought iron frame. The stop was of the same material and of the same diameter as the plunger and was inserted 7.6 cm. into the coil. All curves are due to 10,000 ampere-turns. The curve P_t is due to the plunger electromagnet complete; that marked P_s is due to the solenoid-and-plunger only, and the curve marked P_g is the difference between the above curves. Hence

$$P_g = P_t - P_s \tag{45}$$

represents the pull due to the flux in the air-gap. l_g is the length of the air gap in centimeters.

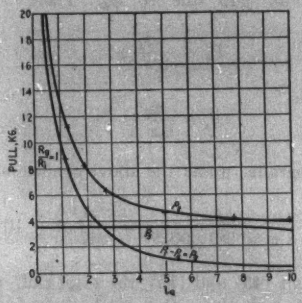


FIG. 34—PULL CHARACTERISTICS OF THE ELECTROMAGNET TESTED

The points marked on the curve P_t are the actual test data for the total pull. The rest of the curve P_t was calculated in the manner described below.

In what follows, the reluctance R_g of the working air gap is assumed to vary directly with the distance between the plunger and the stop. A trial calculation from the test data indicated a nearly-constant reluctance, external to the working air-gap, of 0.17 oersteds. Taking this as a basis, the curve P_t, which agrees closely with the test data, was obtained by adding the calculated air-gap pulls to those due to the solenoid-and-plunger only.

*Part of the following is abstracted from *Electrical World*, Vol. 59, No. 25, p. 1388 (1912).

The m.m.f. for the air gap is

$$F_g = \frac{R_g F_t}{R_g + R_t} \tag{46}$$

wherein F_t is the total m.m.f. (12,570 gilberts), R_g the reluctance of the working air gap, and R_t the sum of the reluctances of the plunger, stop, frame, and non-magnetic joint between the plunger and the frame. Then the flux in the air gap is

$$\phi_g = \frac{F_g}{R_g} \tag{47}$$

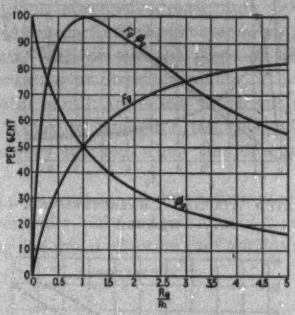


FIG. 35—FORCE, THEORETICAL FLUX AND ENERGY CURVES FOR AIR GAP

The pull due to the flux in the air gap was calculated by equation (**43**).

It has been theoretically proved that the maximum amount of work (initial pull × length of air gap) may be obtained from a plunger electromagnet when the reluctance of the working air-gap is equal to that of the rest of the magnetic circuit.* This is similar to the rule for the maximum wattage which may be obtained in an electrical apparatus connected in series with a line. The general principle is illustrated in Fig. 35, wherein R_t is assumed to be constant. The product of m.m.f. and flux, in the air gap, becomes a maximum when $R_g = R_t$. $F_g \phi_g$ is, in a way, analogous to the e.m.f. multiplied by the current strength.

*E. R. Carichoff, *Electrical World*, Vol. XXIII, pp. 113 and 212 (1894).

The point marked $\frac{R_g}{R_i} = 1$, on the curve P_g in Fig. 34, is where the reluctance of the air gap is 0.17 oersted, which is the same as the calculated reluctance for the rest of the magnetic circuit.

Fig. 36 shows the calculated air gap characteristics of the test

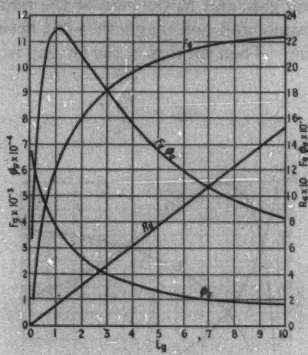


FIG. 36—CALCULATED AIR GAP CHARACTERISTICS OF TEST ELECTROMAGNET

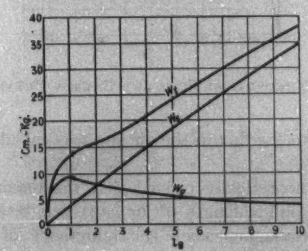


FIG. 37—WORK CURVES OF TEST ELECTROMAGNET

electromagnet. The calculated values of F_g ϕ_g become at a maximum when the air gap is 1.1 cm. in length, which is the point where $R_g = R_i$.

The centimeter-kilograms of work, for varying lengths of air gap, obtained with the test electromagnet, are shown in Fig. 37. W_i is the pull $\times$ distance which was actually obtained with the

complete plunger electromagnet, while W_1 is the actual pull × distance obtained with the coil-and-plunger only. The curve marked W_2 represents the difference between curves W_1 and W_1.

Therefore, the maximum amount of work as defined above which may be obtained with a plunger electromagnet, with a given m.m.f., is not directly dependent upon the equality of the reluctance of the air gap and the sum of the reluctances of the rest of the magnetic circuit.

The amount of work which may be obtained with a plunger electromagnet becomes at a maximum when the range or distance of travel of the plunger times the sum of the pulls, due to the flux in the air gap and to the flux in the plunger coacting with the magnetizing force, become at a maximum.

The latter rule is general and is applicable to all forms of plunger electromagnets, with or without stops or frames, whether designed for alternating or direct currents. When the air gap reluctance and total m.m.f. are of low value, the pull due to the "solenoid effect" may be negligible, but this pull increases with the m.m.f. and is very marked when the air gap reluctance is relatively high.

The designs of alternating- and direct-current plunger electromagnets differ, generally, only in their windings and ferric parts; the law governing the mean effective pull applies to both.

DISCUSSION ON "SOLENOIDS" (UNDERHILL), WASHINGTON, D. C., APRIL 24, 1914.

Charles W. Burrows: I would like to call attention to a few points in which I am not in complete agreement with the author.

In the first place, Tables I to IV used in the calculation of the magnetic field are given* out to the sixth place of decimals. As the assumptions made in the computations did not seem to warrant such precision I recalculated some of the results by a more precise formula, as follows:

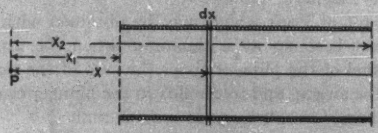


FIG. 1

The magnetic field at any point on the axis of a solenoid is given by the equation

$$H = 0.2\,\pi\,n\,I \int \frac{r^2}{(r^2 + x^2)^{3/2}\,dx} \tag{1}$$

where

H = magnetizing force of solenoid
n = number of turns per cm.
x = axial distance of element of coil
r = radius of coil
I = current in amperes in coil.

The integration of equation (1) gives

$$H = 0.2\,\pi\,n\,I \left[\frac{x}{\sqrt{r^2 + x^2}}\right]_{x_1}^{x_2}$$

$$= 0.2\,\pi\,n\,I \left[\frac{x_2}{\sqrt{r^2+x_2^2}} - \frac{x_1}{\sqrt{r^2+x_1^2}}\right] \tag{2}$$

where x_1 and x_2 (Fig. 1) are the distances from the point where H is measured to the two bounding planes of the solenoid.

If we measure x in terms of r and let

$$\alpha_1 = \frac{x_1}{r} \text{ and } \alpha_2 = \frac{x_2}{r}, \text{ then}$$

$$H = 0.2\,\pi\,n\,I \left(\frac{\alpha_2}{\sqrt{1 + \alpha_2^2}} - \frac{\alpha_1}{\sqrt{1 + \alpha_1^2}}\right) \tag{3}$$

*In the paper as originally printed.

The quantity enclosed in parentheses is a more exact expression for what is called h in the paper.

$$h = \left(\frac{\alpha_2}{\sqrt{1+\alpha_2^2}} - \frac{\alpha_1}{\sqrt{1+\alpha_1^2}}\right) \tag{4}$$

At the center of a coil one radius long

$$\alpha_2 = +\frac{1}{2}$$

$$\alpha_1 = -\frac{1}{2}$$

$$h = \left(\frac{\frac{1}{2}}{\sqrt{1+\left(\frac{1}{2}\right)^2}} - \frac{-\frac{1}{2}}{\sqrt{1+\left(\frac{1}{2}\right)^2}}\right)$$

$$= \frac{2}{\sqrt{5}} = 0.894$$

and not unity as given in the table.

For an adjoining similar solenoid

$$\alpha_1 = \frac{1}{2}$$

$$\alpha_2 = \frac{3}{2}$$

$$h = \left(\frac{\frac{3}{2}}{\sqrt{1+\left(\frac{3}{2}\right)^2}} - \frac{\frac{1}{2}}{\sqrt{1+\left(\frac{1}{2}\right)^2}}\right)$$

$$= \frac{3}{\sqrt{13}} - \frac{1}{\sqrt{5}} = 0.385$$

and not 0.363560 as given in the table.

Consequently in Table I, page 487, the column headed h_a should be corrected as follows:

m_5	h_a as given	h_a as corrected
1	0.353560	0.385
2	0.089443	0.096
etc.	etc.	etc.

These errors are transferred to Table II on page 488, where column 1 should be corrected as follows:

Column 1 as given	Column 1 corrected
1.0000000	0.894
1.353560	1.279
1.443003	1.376

The most accurate figure in this table is in column 6, where the number 1.992872 should be replaced by the true value 1.968.

All these errors are due to the assumption that the formula for the field at the center of a single turn holds for a layer whose length is equal to the radius. The errors may be eliminated or reduced by taking as elements shorter lengths, as Mr. Underhill has done in his book on "Solenoids," or individual turns, as Thompson has done.

Even though suitable accuracy is obtained in this way, I do not believe the method is valuable, since the desired results can be obtained more simply otherwise.

Instead of calculating the force due to each individual element of a solenoid we may approach the matter from a somewhat different point of view.

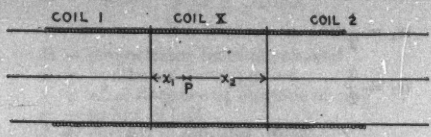


FIG. 2

Any finite solenoid as coil X (Fig. 2) may be considered as having been made from an infinite solenoid by removing the two infinite portions represented by coil 1 and coil 2. The magnetic field within the solenoid X at a point P on the axis, distant from its bounding planes by x_1 and x_2, respectively, is then equal to the field due to the original infinite solenoid minus the fields produced at the point P by the coils 1 and 2. The field due to coil 2 is given from equation (3) by making $\alpha_2 = \infty$.

Then

$$H_2 = 0.2\,\pi\,n\,I\left(1 - \frac{\alpha_1}{\sqrt{1+\alpha_1^2}}\right) = 0.2\,\pi\,n\,I\,h_2$$

Similarly, the field due to coil 1 is

$$H_1 = 0.2\,\pi\,n\,I\left(1 - \frac{\alpha_2}{\sqrt{1+\alpha_2^2}}\right) = 0.2\,\pi\,n\,I\,h_1$$

where α_1 and α_2 are the distances, in terms of the radius, of the point P beyond the free ends of the coils 2 and 1 respectively.

For the original infinite solenoid

$$H = 0.2\,\pi\,n\,I \times 2$$

so that for the finite coil (X),

$$H = 0.2\,\pi\,n\,I\,(2 - h_1 - h_2)$$

h_1 and h_2 may be called the end corrections and are tabulated in Table I and shown in Fig. 3.

TABLE I

Showing the end effects of a solenoid, where h_1 and h_2 refer to the corrections for the two ends of the solenoid.

0.0	1.0000
0.1	0.9005
0.2	0.8039
0.3	0.7126
0.4	0.6286
0.5	0.5527
0.6	0.4855
0.7	0.4266
0.8	0.3755
0.9	0.3310
1.0	0.2928
1.5	0.1681
2.	0.1056
3.	0.0511
4.	0.0300
5.	0.0195
6.	0.0136
7.	0.0102
8.	0.0080
9.	0.0064
10.	0.0050

The data of this table are plotted in Fig. 3.

To use this table let us calculate the field at a point on the axis of a coil ten radii long at a point two radii distant from one end. From the table,

$$h_2 = 0.1056$$
$$h_3 = 0.0080$$
$$h_2 + h_3 = 0.1136$$
$$2 - 0.1136 = 1.8864$$

so that

$$H = 0.2\,\pi\,n\,I \times 1.8864$$

On page 491 we find "* * * * * conceiving the m.m.f. as consisting of two components, one of which produces the magnetizing force to magnetize the plunger while the other component produces the magnetizing force to coact with the flux in the plunger and thus cause attraction."

Instead of considering that the plunger is fully magnetized and the m.m.f. is divided into two portions, one of which magnetizes but does not attract and the other of which attracts but does not magnetize, I look at the matter somewhat differently.

I consider that the entire m.m.f. is used to magnetize the plunger and that the entire m.m.f. is also used to react on the magnetized plunger. To be sure, the magnetic induction produced is not the greatest possible for the given m.m.f. because of the relative positions of the solenoid and plunger, and also because of the self-demagnetizing influence, which has been neglected entirely.

The formula (**35**) on page 493 is not strictly correct. This is evident when we consider the special case of the bar located symmetrically within the solenoid. According to the formula the pull in this position should be a maximum. However, we know from experimental evidence that the pull is zero. It would be better to say that the pull is proportional to the product of the field strength and the leakage from the bar. This is equivalent

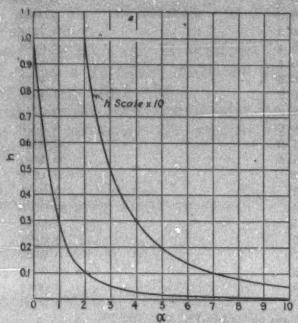


FIG. 3—CURVE SHOWING THE VARIATION OF α AND h.

to saying that the pull is due to the reaction between the magnetic field and the free poles.

Fig. 26 presents some anomalies. When the plunger is inserted almost to the far end of the solenoid the figure shows that 10,000 ampere-turns give rise to a greater induction than 40,000. As it is obviously impossible that the larger m.m.f. should give rise to the smaller induction, the premises on which these data were calculated must be in error. Equation (**37**), page 496, used in the calculations of the data for these curves, is open to the same objections as those brought against equation (**35**). The error due to assuming that this equation holds, may be enough to account for the discrepancy.

E. R. Carichoff: In his reference to my paper published in 1894, what Mr. Underhill mentions is only a corollary to my proposition, and this corollary is true only when μ is supposed to be constant. My proposition deals with certain definite assumptions, one of which is only approximately true—viz., the assumption of no leakage.

I will give here substantially the discussion—Having given a magnet of definite length and cross-section, an air gap of given length, and any constant magnetomotive force, to find the polar area that will give a maximum force.

In the formulas, A, L, B and H represent respectively the area, length, induction and magnetic force for the air gap, and a, l, b and h the same quantities for the iron, the flux in the air gap and in the iron being assumed to be the same.

$$P \propto A\,B^2 \propto A\,H^2 \tag{1}$$

$$\frac{dP}{dA} = 2\,A\,H\,\frac{dH}{dA} + H^2 = 0$$

for maximum force, or

$$2\,A\,\frac{dH}{dA} + H = 0 \tag{2}$$

The condition of constant m.m.f. is

$$HL + hl = \text{constant.} \tag{3}$$

The condition of no leakage is

$$AH = a\,b \tag{4}$$

By differentiating (3) and (4) with respect to A and substituting in (2) we have the relation

$$\frac{a\,db}{l\,dh} = \frac{A}{L} \tag{5}$$

This means that the tangent to the curve representing the permeance of the iron equals the permeance of the air gap; and further, if μ is constant it means reluctance of iron = reluctance of air gap.

Again, if the polar area is constant and the length of the air-gap is made a variable, the other conditions remaining as before, and the problem is to find the length of air gap that will make the product of force times length of air gap a maximum, we have

$$W \propto A\,B^2L = A\,H^2\,L \tag{6}$$

and

$$\frac{dW}{dL} \propto 2\,LH\,\frac{dH}{dL} + H^2 = 0$$

maximum work, or

$$2\,L\,\frac{dH}{dL} + H = 0 \tag{7}$$

By differentiating (3) and (4) with respect to L and substituting in (7) we get the same relation given in equation (5).

Mr. Frank Fowle has described certain investigations made by him on telegraphic relays which resulted in securing greater force by means of enlarged poles, but I believe that, generally, designers have not given sufficient attention to this point.

There is another relation that I have found most useful, and that is—what diameter of core should be used to get maximum force when the air gap is inside the coil and the outside diameter of the coil is fixed and the heating in the coil is a constant.

Oliver Heaviside, in his "Electrical Papers," Chapter XVII, page 103, gives the relative diameters of core and coil as

$$\frac{y}{x} = \frac{\sqrt{5} - 1}{2} \tag{8}$$

where y is the diameter of the core and x is the outside diameter of the wire winding, but not including the outside wrapping.

In this equation no allowance is made for space between the winding and the core. My practise is to allow 0.2 inch on each side of the core. With this constant inserted, the equation becomes

$$x = \frac{1}{2}\, y + \sqrt{(y + 0.4)^2 + \left(\frac{1}{2}\, y\right)^2} \tag{9}$$

As an approximation correct within a small percentage I use the following:

$$\frac{x - 0.4}{y} = 1.6 \tag{10}$$

It is interesting to note that values of 3.6 for x and 2 for y satisfy both equations (**9**) and (**10**).

In these equations μ is supposed to be constant.

C. R. Underhill (by letter): The method described by Dr. Burrows for finding the magnetizing force along the axis of a solenoid is simple and very interesting. It is stated on page 483 of the paper that the calculated values are only approximate. Therefore, a comparison of the values obtained by Dr. Burrows's method and those obtained by the approximate method of the author will be of interest. In the following table are shown the ratios which are obtained by dividing the author's values in Table II of the paper by those calculated by the method of Dr. Burrows.

Section of reference a / m	1	2	3	4	5	6	
1	1.12						
2	1.06						
3	1.05	1.025	(middle section)				
4	1.05	1.02					
5	1.05	1.02	1.017	(middle section)			
6	1.045	1.02	1.015				
7	1.045	1.02	1.015	1.012	(middle section)		
8	1.045	1.02	1.015	1.012			
9	1.045	1.02	1.015	1.012	1.011	(middle section)	
10	1.045	1.019	1.015	1.011	1.011		
11	1.044	1.017	1.013	1.011	1.011	1.01	(middle section)

Anyone wishing to work closer than one or two per cent should, therefore, calculate the values by Dr. Burrows's method. Those engaged in practical design can use the data directly from the curves in Figs. 15 to 24, because it is impossible, with the present known methods, to predetermine the pull between a solenoid and plunger at all points in its travel, with a greater accuracy than several per cent. The values for the end sections are of little importance because a long-range solenoid usually consists of more than two sections.

As to the demagnetizing action of a solenoid on its plunger, this is briefly touched upon at the bottom of page 480 and again on page 501 of the paper. For all practical purposes, the core or plunger can be assumed to be very long, and the demagnetizing action ignored for ordinary flux densities. The demagnetizing effect is only noticeable when uneconomical magnetizing forces are used. Fig. 25, page 496, shows this. The plunger was thoroughly saturated with 10,000 ampere-turns, and at this value the demagnetizing effect is scarcely noticeable. Even with 20,000 ampere-turns it is not serious. As the magnetizing force is increased, the plunger is saturated for greater portions of its length, so that when abnormal magnetizing forces are used the effect is noticeable.

The author's reference to the important law of Mr. Carichoff, which is based on the assumption of no leakage, was given to emphasize the importance of magnetic leakage in all electromagnets of the plunger type, since the leakage increases the flux in the plunger and, consequently, the pull. In electromagnets of the horseshoe type and modifications of the same, the pull due to magnetic leakage is lost because the relative positions of the coils and cores are unfavorable, and, furthermore, they are usually fastened together.

The characteristics of alternating-current electromagnets are easily explained when magnetic leakage is considered. Many otherwise excellent papers and articles have been written upon the subject of electromagnets, but, in nearly all cases, no leakage is assumed: consequently, their value is lessened.

The characteristics are best predetermined from the standpoint of energy, but, until the permeances of the leakage paths for different positions of the plunger are thoroughly worked out, only the average mechanical force or pull can be calculated, and this is of little use to designers of electromagnets, excepting in the design of electromagnetic hammers and the like; it does not throw light on the mechanical forces or pulls at all points throughout the entire range of travel of the plunger, and the latter is usually a very important consideration.

Presented at the 294th meeting of the American Institute of Electrical Engineers, Washington, D.C., April 24, 1914, under the auspices of the Electrophysics Committee.

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SOME INVESTIGATIONS ON LIGHTNING PROTECTION FOR BUILDINGS

BY L. A. DE BLOIS

ABSTRACT OF PAPER

A description is given of investigations conducted for a large manufacturer of explosives to determine upon a suitable system of lightning protection for buildings containing explosives. The work is divided into the following sections:

(1) An analysis by oscillograph of the secondary currents induced by actual lightning discharges in vertical earthed conductors, the results seeming to indicate that such currents are non-oscillatory and aperiodic, though occurring in either a negative or positive direction. An attempt is made to explain the phenomena generally attributed to high, frequency oscillations by the existence of unidirectional waves of almost vertical front.

(2) An investigation of the primary effects of a 20-in. spark in air, having the same essential characteristics as those attributed to lightning, when applied to a model protective system consisting of isolated vertical conductors surrounding a small building.

(3) An investigation of the secondary effects produced under the above conditions, which are considered to be static inductive rather than dynamic inductive.

A brief description is given of a general protective system recommended for explosives buildings.

IT IS the purpose of this paper to describe the results of a study made in an effort to develop a system of lightning protection for explosives manufacturing buildings and magazines which would insure at least some measure of protection, rather than a possible increase in risk—as unfortunately seems to have been the case with some so-called "protective systems." Since such systems have been based on speculative theory as to the actual character of lightning or on the behavior of model buildings when subjected to spark discharges supposed to bear close relationship to the natural phenomenon, an effort was made to obtain, if possible, some further and more dependable information, that would furnish not only a better understanding of the actual conditions to be met, but also permit more reliable reduced-scale laboratory experiments.

Investigation of Lightning Discharges

Secondary currents induced in vertical earthed conductors by the passage of nearby lightning discharges to earth presented themselves as a possible clue to the nature of the current in the actual discharges. Two 103-ft. (31.3-m.) wireless towers, situated on the roof of a 123-ft. (37.4-m.) office building, were utilized. The yards, 170 ft. (51.8 m.) apart, subtended a horizontal plane area of 5100 sq. ft. (469 sq. m.) represented by 21 horizontal and approximately parallel conductors. This large plane area, acting as condenser against the upper air, was found necessary in order to permit the reception of induced currents of sufficient magnitude for analysis by the instruments available. The conductors were divided into two groups of 19 and 2, to serve as "collector-aerial" and "pilot" respectively, each set being cross-connected at the ends and provided with two 180-ft. (54.8-m.) leads running obliquely downward to the laboratory on the roof. The leads were provided with horn arresters just outside the building and were connected on the inside to switches operated by ropes. This arrangement of aerials gave an excellent installation, well above the ground, with an unobstructed view of the country in all directions; thereby insuring freedom from wave-absorption by grounded conductors nearby. A ground connection was secured by a heavy cable bolted to the steel framework of the building. The natural wave length of the "collector-aerial" was found to lie between 700 and 800 meters.

The instruments used consisted of a wireless receiving equipment with various detectors, an indicating "ceraunoscope" (needle detector with electric alarm decoherer), an adjustable spark-gap, an 800-volt multicellular static voltmeter, and a double-element permanent-magnet oscillograph, modified by the addition of field coil and motor drive for the revolving mirror. The wireless equipment was used on the collector-aerial for storm prediction as described later, the "ceraunoscope" and static voltmeter between the pilot-aerials and ground to indicate respectively the occurrence of heavy discharges and the variation in static potential, the spark-gap between either aerial and ground as an alternate method of indicating the passage of discharges, and the oscillograph between the collector-aerial and ground to furnish a means for analyzing the induced currents. The low resistance, inductance and capacity factors of the latter instrument rendered it satisfactory for this purpose when the

usual gold-leaf fuses were replaced by solid metal. Its periodic time (5000-6000), on the other hand, would have been too low to permit the measurement of high frequencies, had they been encountered.

The importance of storm prediction by the wireless equipment was emphasized by the necessity of recording all the comparatively few discharges which were sufficiently heavy or sufficiently close to induce measurable currents in the aerials, a condition aggravated by the transitory nature of the storms and by their comparative infrequency. As a matter of fact, of fourteen electrical storms in the summer of 1913, only six were of a character suitable for observations, and the period during which such work could be performed averaged less than twenty minutes. It was found that after some experience with the sound produced in the wireless receivers by the waves propagated by lightning discharges, the presence of an electrical storm could be predicted from 8 to 10 hours before its possible advent, and hourly observations on their intensity would generally indicate whether it was approaching or merely passing through the field of the instruments. Assuming a rate of storm-travel of 25 to 40 miles (40.2 to 64.3 km.) per hour, it would thus seem possible to detect the presence of a traveling storm between 200 and 400 miles (321 to 643 km.) away.

Until the storm was close at hand, differences of potential between collector-aerial and the ground occurred only coincident with distant flashes of lightning, but were often sufficient to jump a small air-gap or administer a sharp shock, unless the wires were grasped firmly in the hand before the switch was closed. As soon as the edge of the storm clouds was nearly overhead, however, the aerials when disconnected from ground commenced to assume strong static charges, as indicated by the static voltmeter or spark-gap. Such charges always occurred with electrical storms, though less prominently where intercloud lightning prevailed, and also often occurred with cumulus clouds that gave no other indication of their electrical character. In such cases the aerials acted as condensers of low capacity charged to high potential, and if connected to ground through the oscillograph, discharged at the natural frequency of the circuit. As this was approximately 400,000 per second, while the natural period of the oscillograph was only 5000-6000, such discharges did not affect the elements, though the addition of series inductance rendered them clearly visible on the revolving

mirror. If the spark-gap was substituted for the oscillograph at such times, sparks of discharge passed fairly uniformly for considerable periods until a lightning stroke took place, when they succeeded each other so rapidly as to resemble momentarily a single arc of some duration. At such times the static voltmeter on the "pilot" aerial departed from its usual slow swinging variation by a sudden upward swing, sometimes from zero and sometimes preceded by a gradual rise. This was generally followed by a momentary subsidence to zero.

The first attempts to use the oscillograph for indicating currents induced by lightning discharges during 1912 were not encouraging, no indications being obtained, mainly on account of insufficient capacity in the aerials, but after considerable practise with the instrument on high-frequency discharges, and various modifications in the aerials and apparatus, visible indications on the revolving mirror were noted during the first storm of 1913. These were obtained only during the passage of heavy discharges comparatively close to the laboratory. With especially violent discharges the static voltmeter on the "pilot" aerial often arced over, as well as the oscillograph switches, and in several cases, the horn arresters outside the laboratory. The handling of the equipment had to be done by means of well-insulated poles, or only after first disconnecting and grounding the aerials—in fact the whole work of observation was far from pleasant, especially at night, the noise of the thunder and rain being often deafening and accompanied by numerous sparks in the apparatus, and at times by sharp hissing brush discharges presumably from the building itself, and the general discomfort was increased by the possibility of interruption to the lighting service and power supply from induced effects. All these conditions naturally contributed to the difficulty of securing permanent and conclusive records.

As the collector-aerial could not be tuned to the incoming wave, and responded only with forced oscillations, great difficulty was encountered in obtaining sufficient induced currents for satisfactory indications, except in the case of unusually heavy discharges nearby. Otherwise, the photographic records were exceedingly minute, and were moreover obscured by a heavy zero-line, resulting from the continuous rotation of the oscillograph film at high speed for the prolonged period necessary to insure the reception of a record—there being of course no means of foretelling the occurrence of a heavy discharge. Consequently

visual observations on the revolving mirror were found to be more satisfactory, though of course producing no confirming records.

In August 1913 a storm of unusual duration and intensity occurred and for a time appeared to be central over the locality. Three photographic records in particular were obtained, which are reproduced in Fig. 1 as largely typical of the lesser records obtained previously.

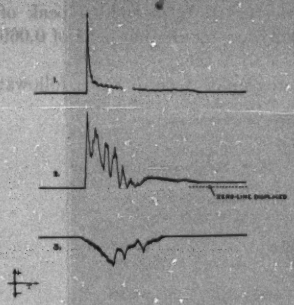


FIG. 1—LIGHTNING OSCILLOGRAMS STORM OF AUGUST 23, 1913

Referring to Fig. 1, curve (1) is a typical example of a single steep-front discharge from clouds to earth. The rate of initial rise of current is too rapid to be figured with any accuracy from the record. The maximum value of the induced current as recorded on the film was 0.5 ampere (actually probably exceeding this amount), and the peak proper endured 0.0008 sec. The latter part of the decay of the current endured 0.02 sec., giving indications of minor sustained oscillations above the zero-line, occurring with a periodicity of about 15,000 per sec. This effect is unmistakable and, though not previously photographed, had been noted in a few of the discharges observed on the revolving mirror.

Curve (2) is a typical steep-front wave with five main and three supplementary peaks, of which the values are approximately as follows:

	Maxima, Amperes	Duration, Seconds	Resultant Minima, Amperes
1st Peak	0.474	0.0005	0.225
2nd Peak	0.387	0.0015	0.114
3rd Peak	0.305	0.0016	0.069
4th Peak	0.266	0.0014	0.010
5th Peak	0.152	0.0012	0.000
	Total	0.0062	

These peaks are followed by a gradual rise to 0.042 amperes with indistinct indications of sustained oscillations of a higher

periodicity than in (1) for 0.01 sec., gradually dying away to zero. The total duration of discharge was 0.0184 sec.

Curve (3) is a wave of totally different character. The direction of flow is from the earth upwards, but with a gradual rise with indications of oscillations to a maximum of 0.18 amperes, which is reached in 0.0046 sec. The current then starts to decay but in 0.0023 sec. is interrupted by a sudden peak of 0.121 amperes, and again in 0.0025 sec. by another peak of 0.069 amperes. The total duration is 0.0129 sec.

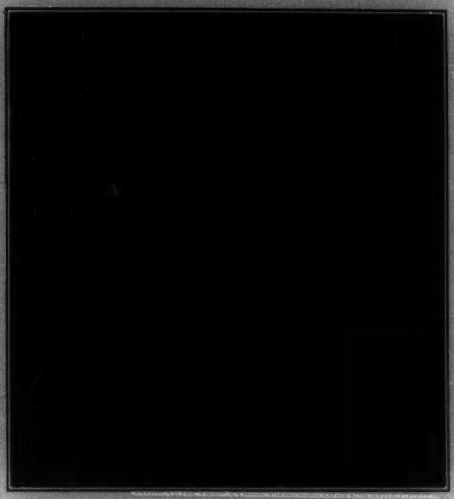
A summary of all other photographic records is as follows:

Total number of separate discharges recorded photographically	50
" " " " " with single peaks	38
" " " " " " multiple "	12
" " " " " " steep wave-front	29
" " " " " " sloping " "	21
Total number of strokes positive (from clouds to earth)	43
" " " " negative (from earth to clouds)	7

Average duration of 38 single peaks	0.00065	sec.
Minimum " " single peak	0.0002	"
Maximum " " " "	0.0016	"
Maximum duration of multiple discharge	0.0034	"
Maximum number of peaks in one discharge	6	"

In this tabulation the three heavy discharges (1), (2) and (3) already discussed in detail are not included, as their measurements were not altogether comparable with the lesser indications obtained during the previous storms. For instance, the single-peaked steep-front wave (1) showed a total duration of 0.0208 sec., but of this the peak only would have been observed in the smaller records. This peak actually endured 0.0008 sec., which agrees fairly well with the average duration of 0.00065 sec. found for the 38 single-peak waves, and we may assume that each of the latter may have had its own prolonged decay similar in general respects to that of (1), but which was obscured by the broad zero-line of the oscillogram.

In no records was there any indication of regular periodic high-frequency oscillations in the induced current. Had they existed, the oscillograph, of which the periodic time was 5000 to 6000, would have failed to respond. This was never the case with heavy discharges to earth nearby, though it did happen, presumably for other reasons, with many purely inter-cloud discharges. Moreover, the static voltmeter could hardly have been expected to respond to high-frequency oscillations as it did in the majority of cases of lightning discharges to earth. On the other hand, it is probable that the currents induced



[DE BLOIS]

FIG. 2—PHOTOGRAPH OF 20-INCH SPARK WITH REVOLVING CAMERA

[DE BLOIS]

FIG. 3—OSCILLOGRAM OF CURRENT IN SPARK FROM OSCILLATION TRANSFORMER SECONDARY

in the collector-aerial followed in a general way at least the variations in the traveling waves of the lightning discharges, since such variations, judging by the oscillograms, involved high values of $\frac{di}{dt}$ only in the case of steep-front waves, and also for the reason that the damping effect of the aerial, whose natural period of vibration was about 400,000, must have been very small. If such was the case, do not the records obtained point to the fact that lightning discharges are essentially unidirectional, non-oscillatory, aperiodic phenomena, especially since the steep wave-front occurring in the majority of such discharges would account for all the usual effects attributed to high-frequency oscillations?

A point in doubt is a suitable explanation for the occurrence of multiple peaks, as in 2, and for the gradual rise of current, as in 3. In the former case, the time intervals between maxima are too short to allow the peaks to be construed as the so-called "related discharges" which are photographed as a single flash by a stationary camera, but as separate discharges along the same path by a camera slowly rotated in the horizontal plane, notably in the work of Dr. B. Walter. Since the current rarely reached zero between maxima, these peaks may represent simply the result of the "progressive break-down" of the atmosphere so clearly defined by Dr. C. P. Steinmetz, that is, of a discharge from point to point. On the other hand, the slow rise of current as in (3), may correspond to the *A* discharge of Sir Oliver Lodge, brought about by the gradual building-up of potential, possibly accompanied by the formation of brush discharges from buildings, etc., brilliant examples of which were noted in the storm during which these oscillograms were taken, or by the formation of striae gradually lengthening and preparing the discharge path. If such were the case, conversely, the *B* or "overflow discharges" of Lodge might correspond to the steep-front waves. It should also be observed that the total duration of discharges as figured from the oscillograms seems greater than usually assumed on the basis of high-frequency effects, and consequently the actual discharge current may be somewhat less than generally assumed on the basis of dynamic effects.

Whatever may be the true explanation of such points as these, it seems reasonable to assume that the most dangerous discharges are those with almost instant rise to maximum value, both

on account of the impact of the stroke and the possibility of dangerous secondary effects.

Investigation of Primary Protection

For the laboratory work a loose-coupled oscillation transformer was used with Leyden jars and rotary spark-gap, energized by a three-kw. 60-cycle magnetic leakage type transformer. Interruptions took place in the condenser circuit 527 times per sec., and a 42-in. (1.07-m.) spark of good substantial character was obtained from the secondary transformer terminals, though for practical purposes this was reduced to 20 in. (0.5 m.) during the greater part of the work. Fig. 2 shows photographs of this spark taken with a revolving camera, indicating the occurrence of groups of sparks for each half-wave of the 60-cycle supply, while Fig. 3 shows an oscillogram of the current in the discharge. This consists of one main half-wave, either positive or negative, with steep front and with an average duration of 0.00046 sec., followed by one or two suppressed half-waves. This agreement with the oscillograms of lightning discharges in the matter of steep wave-front and short duration was considered sufficient excuse for the employment of the 20-in. (0.5-m.) spark in the work to follow. It might be added that the discharge presumably corresponded to Lodge's *B* type, that is, was produced suddenly and not by a gradual building-up of potential, and in conformance with this struck equidistant ball and point electrodes impartially.

Preliminary work with this spark, directed vertically downward from points (called "cloud-points") pendent from a suspended metal "cloud", to a metal ground-plate or a box of dry or moistened earth on which was placed the model of a small building constructed of pasteboard with metal roof and interior metal apparatus, pipe lines, electric lines, etc., on a scale of 1 in. to 20 ft., with four isolated vertical lightning rods placed a short distance from its corners, led to the following general conclusions, some of which are of course self-evident:

(a) The building was in the greatest danger when the discharge took place from one cloud-point placed directly above it.

(b) The lower this cloud-point, the more likely the building was to be struck, especially if the lightning rods were low or widely separated.

(c) An increase from one to four cloud-points merely increased the number of rods likely to be struck simultaneously.

(d) The closer the cloud-point to the building, the greater the number of rods which were likely to be struck simultaneously.

(e) With one cloud-point, the farther apart the rods, the fewer were struck simultaneously.

(f) With outside lightning rods of a proper height and at a proper distance, a model similar to the one tested could be protected with apparently 100 per cent efficiency.

(g) With low or widely separated rods the introduction of a metal roof, not grounded, seemed to increase slightly the probability of the building being struck, and at the same time seemed to increase the probability of more than one rod being struck simultaneously.

(h) Grounding the roof, if the protection was poor, seemed to increase the probability of its being struck, but if the protection was good such grounding seemed to have little or no effect.

(i) The introduction of an intermediate cloud below the main cloud seemed to render one rod more likely to be struck if the intermediate cloud was high, but when low this effect was more or less neutralized.

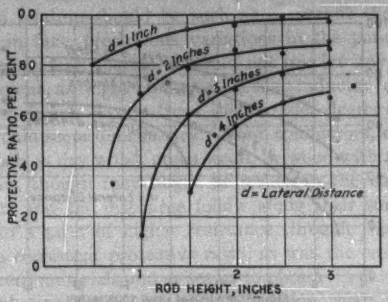


FIG. 4—ROD EFFICIENCY—EFFECT OF HEIGHT AND SPACING

(j) While a horizontal plate or a mesh screen across the tops of the rods gave perfect protection, a girdle, when the rods were too widely placed or too low, was not entirely effective.

These conclusions, though based on a length of discharge equivalent to only 700 or 800 ft. (213 or 243 m.), furnished the necessary information for the arrangement of apparatus in the following tests, which will be summarized as briefly as possible and discussed in detail later.

Protective Efficiency of Outside Rods. Four small vertical wire rods of equal length were set up symmetrically on a metal ground-plate, equidistant from a central rod which represented the object to be protected and was adjusted until its height was just sufficient to avoid being struck by any of the discharges from the cloud-point directly above. This height expressed

as a per cent of the height of the outside rods was termed the "protective ratio" of the latter, and is plotted in Fig. 4 for a fixed cloud-point height of 20 in. (0.5 m.) above the ground-plate with varying rod-heights and lateral spacing from the central rod, and in Fig. 5 with varying cloud-point height for different combinations of rod-height and lateral spacing.

Effect of Imperfect Grounding of Rods. The four outside rods were raised so as to leave slight air-gaps between them and the ground-plate. This was tried for different rod-heights and air-gaps, but the effect on the protective ratio was almost exactly equivalent to that produced by cutting off from the tops of the rods an amount equal to the length of the air-gap.

Effect of Conductivity of Rods. A long series of tests was

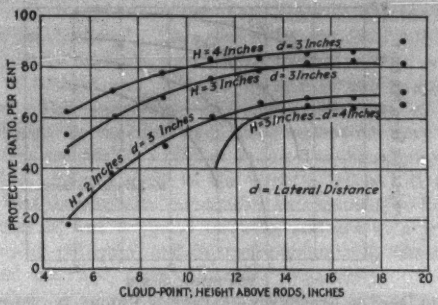


FIG. 5—ROD EFFICIENCY—EFFECT OF CLOUD-HEIGHT

made with rods of different materials, of different diameters, and with rods in which were inserted small inductances. The protective ratios of good conductors such as wires of different metals of various diameters were almost identical, and even the insertion of inductance, with and without iron in the magnetic circuit, did not seriously affect their efficiency. Poor conductors, however, such as green and dry wood, wood moistened with water, acids, etc., or rendered partially conducting by a lead pencil mark or by a carbonized streak resulting from a previous discharge, though frequently struck, failed to consistently protect any low object in their vicinity—even the ground-plate itself. Also, in contradistinction to good conductors, when struck they arced over for their entire length,

wood being splintered and eventually ignited after the moisture and volatiles had been driven off or consumed.

Discussion of Results. The function of a lightning rod is presumably two-fold:

(1) To form a projection from the surface on which the lower charge resides, extending sufficiently above the objects to be protected, and thus present to the clouds a salient point having the same relative potential as the lower surface.

(2) When struck, to carry off the current of discharge without potential differences in its length sufficient to cause the discharge to split off or be diverted to nearby objects.

As regards the first function, it is evident that the rods, in order to maintain the same potential as the lower surface, must be of conducting material and should be preferably in direct electrical contact with that surface. Their conductivity and potential relation should be such as to permit their following sudden, in fact, precipitous variations in the potential of the lower surface and therefore should not involve any appreciable time-element, as might be the case if high inductance or capacity were introduced. Aside from this, a high degree of conductivity would seem unnecessary. Poor conductors, on the other hand, such as dry wood, green wood, or wood with small wetted perimeter, though they might be struck in the natural course of events and the discharge follow along their surface in preference to a path of higher resistance through the air, would show no consistent protective ratio, as was the case in the tests on different materials and as seems to obtain in nature for trees.

In order to fulfil the second function, high conductivity with low inductance seems imperative, though, where isolated rods could be used, the effect of lateral spacing should be considered; thus if the distance from rod to building was as great as the height of the rod, it would seem that a rod of the minimum resistance to resist fusing could be used.

As regards protective ratio, it seems probable that the rods are nothing more than shunt-paths for the building and its interior equipment. If the latter is in direct contact with the lower surface of charge, the rods should also be in such contact or should be increased in height somewhat more than the equivalent distance. Theoretically the former seems preferable, as one would be led to believe that rods not in direct contact with the lower surface, though of good conductivity, might under some circumstances lag behind the changes in potential of the lower surface and so suffer a loss in efficiency, though

this was not borne out by the tests on the effect of imperfect grounding. On the other hand, it is uncertain exactly what the lower surface of charge is. It is presumably not the earth's surface, unless wet; it may be the surface of permanent moisture, though well-authenticated cases of discharges passing down mines, deep wells, etc., seem to point to the existence of even lower charges; in any case it is probably of good conductivity, as there seems to be no evidence of "inter-earth"—corresponding to inter-cloud—discharges.

The curves for protective ratio tend towards a constant value independent of cloud-height, seeming to indicate that only the lowest part of the path of discharge is affected by the rods. The geometrical relation between the length of the discharge path from the cloud-point to the building and from the cloud-point to the rods is given by the formula

$$H_r = \frac{d \tan a}{2} + H_b$$

where H_r = height of rod in feet.
H_b = height of building in feet.
d = lateral distance from highest point of building to rods, in feet.
a = angle subtended from cloud-point by rod and highest point of building.

This obtains only for small values of (a) but was found to agree with the experimental results by the addition of a constant $K = 0.11$, making the formula

$$H_r = d\left(\frac{K + \tan a}{2}\right) + H_b$$

It seems applicable to the condition of four rods surrounding a building where $d =$ or $< H_r$. It should be noted that it involves no factor for cloud-height other than in the angle (a) and therefore indicates that the results of laboratory tests on protective ratio, etc., might be applicable to natural conditions if the scale of reduction was observed.

Probability of Being Struck. To test the efficacy of the usual argument that lightning rods "attract" lightning and so increase indirectly the danger to the building, a long series of tests were performed directly to scale, on a basis of a minimum length of lightning discharge of 3000 ft. (914 m.) in mountain-

ous districts. Very small models of the building selected (48 by 32 by 41 ft. or 14.6 by 9.7 by 12.4 m. actual) were placed centrally on a cardboard target representing a circular area of 600 ft. (182.8 m.) radius, and this on a somewhat larger ground-plate with cloud-point directly above. The "probability of being struck" was considered to be the number of discharges that fell entirely or in part on the building, lightning rods or within the area subtended by the latter, and was expressed as a percentage of the total strokes falling within the 600-ft. (182.8-m.) radius.

Summarizing the results, it would seem that the erection of a building of non-metallic construction of the size in question, without contents, increased the danger to the plane area only slightly (4 per cent)—until the building was wet, when the "probability of being struck" was increased 32 per cent (net). If a metallic building was erected instead, the "probability of being struck" was increased 58 per cent, or if the building was grounded, 62 per cent. When metal apparatus was installed in a non-metallic building the "probability of being struck" was increased 12 per cent to 50 per cent depending on the height of the apparatus, and if the apparatus was grounded 26 per cent was added in the case of the lower equipment but apparently nothing in the case of the higher equipment. On the other hand, the addition of a short metal ventilator to the grounded apparatus increased the "probability of being struck" 30 per cent more.

When a metal roof was added to a non-metallic building containing metal apparatus the "probability of being struck" increased only slightly, whether the building was wet or dry, but when this roof was grounded, the "probability of being struck" was increased 12 per cent to 56 per cent, depending (inversely) on the height of the grounded metal apparatus inside.

With a non-metallic building with non-grounded metal apparatus and four outside lightning rods 70 ft. (21.3 m.) high and located about 50 ft. (15.2 m.) from the corners of the building, the "probability of being struck" was increased 38 per cent to 54 per cent, depending on whether the building was wet or dry. With a grounded metal roof installed, the "probability of being struck" was increased only 12 per cent, and if the metal ventilator were installed the net increase in "probability of being struck" would probably have been even less.

It is these latter conditions that are of particular interest in determining how much the danger from lightning to the building in question, which was of non-metallic construction, was increased by the erection of rods and apparently in this case the rods "attracted" about 10 per cent to 50 per cent more strokes. On the other hand, if the building had had a metal roof, if it were equipped with metal apparatus reaching nearly to the top, or if its exterior were wet with rain, the effect of the rods would be to add very little to the "probability of being struck." Moreover, it should be noted that these tests were made not only under the conditions of an isolated building on a plane area, but also with the cloud-point directly above the building—a combination very unlikely to occur in nature.

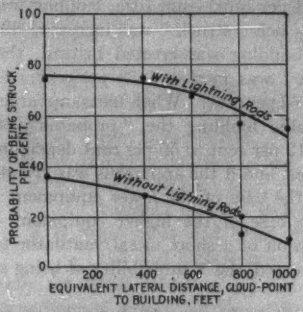


FIG. 6—PROBABILITY OF BEING STRUCK—EFFECT OF CLOUD DISPLACEMENT.

The effect of the position of the cloud-point is shown in Fig. 6, in which the "probability of being struck" is plotted against the horizontal distance from cloud-point to building.

INVESTIGATION OF SECONDARY EFFECTS

In order to reproduce secondary effects in a model building on a scale sufficiently large to be visible, an arbitrary standard of 1 in. (2.54 cm.) to 2 ft. (60.9 cm.) was adopted. This allowed the use of a model of sufficient size to permit the construction of interior apparatus with reasonable accuracy of detail, and, though the relative length of cloud discharge was diminished in proportion, it was felt that this, while increasing the intensity of static inductive effects, would not affect dynamic inductive

effects, since in any event the upper part of a vertical discharge would have little influence because of the narrow angle subtended by it. On the other hand, for dynamic inductive effects it was desirable to have the current of discharge as great as possible and the factor $\frac{di}{dt}$ as high as that of lightning.

The model building was constructed of wood with one side open and was completely equipped with metal apparatus, including pipe lines, electric lines, etc., extending for some distance outside, all metallic parts being separately removable and practicable to interconnect and ground. It was placed directly on an extensive ground-plate with the metal "cloud" above. Secondary discharges were noted by eye or by the use of a small exploring spark-gap.

Static Inductive Effects. Tests were made without direct discharge other than brush from the cloud. Secondary brush and spark discharges were noted inside the building and the following somewhat obvious general conclusions were reached:

(a) All conducting surfaces not thoroughly grounded, when exposed to the influence of a charged cloud immediately overhead, acquire a potential against ground which increases with the height of the conducting surface above ground.

(b) A difference of potential will exist between all conducting surfaces not bearing the same average spatial relation in the electrostatic field to ground or to nearby grounded objects. Such average spatial relation is determined by their shape and size as well as distance from ground or grounded objects.

(c) Conducting surfaces in a vertical plane which would acquire practically no potential from their position in the electrostatic field may acquire a charge from the influence of adjacent objects.

(d) The grounding of a conducting surface generally increases the danger of sparks from adjacent non-grounded surfaces.

(e) Interconnecting adjacent conducting surfaces can prevent differences of potential between them but may increase the tendency of the lowest surface (relative to ground) to arc to ground.

(f) Discharges tend to take the shortest path, and large surfaces in the horizontal plane should be interconnected or grounded at more than one point.

(g) A grounded roof acts as shield for objects beneath it and even when poorly grounded diminishes the potential between them, but potentials can be introduced below it by conductors which extend inward from the outside, provided they are of sufficient capacity.

(h) Secondary discharges may occur from the sudden charge of an overhead cloud or from its discharge. The discharge in any case follows the natural frequency of the circuit and consequently may become oscillatory, though this condition is improbable in the ordinary interior apparatus, excepting only electrical equipment.

(i) The effect of adjacent lightning rods is to diminish the intensity of secondary effects, though for outside rods of reasonable height and spacing, the "secondary static protective ratio" is practically inconsiderable.

Dynamic Inductive Effects. Tests for such effects were made both with the discharge from the secondary of the oscillation transformer and with the primary current of the latter carried down a vertical rod close to the model building. In the latter case the current was calculated to be approximately equivalent to a lightning discharge of over 100,000 amperes maximum value with a half-wave duration of approximately 0.000005 sec. —a condition far more severe than any indicated by the oscillograph storm-records. In no case could dynamic inductive sparks be obtained, though occasional static sparks were produced in unbalanced partially closed loops. This failure was attributed to the comparatively small area of the partially closed loops formed by the various equipment and by the fact that neither these loops nor vertical conductors could be "tuned" to the magnetic waves and consequently responded only with forced oscillations. When it is considered that with a high aerial of large capacity such as described in the first part of this paper, currents of only a fraction of an ampere were obtained with comparatively nearby discharges, it does not seem unreasonable that the dynamic inductive effects in a small model building should be insignificant as compared with the static inductive effects.

General Recommendations for Protective Systems

As a result of this work, the general recommendations for the protection of manufacturing and storage buildings where such protection is justified either by the impracticability of the operators always leaving the building during a storm, or by the value of the building or the character of its contents, consisted in a series of vertical isolated rods of iron pipe placed outside and surrounding the buildings, and grounded to annular conductors buried in the earth at least as low as the water pipes, with extensions running out radially at the corners; metallic roof projections such as ventilators to be eliminated as far as possible; metallic roof and floor coverings to be grounded at their salient angles; overhead pipe-lines and other metal conductors to be grounded at intervals and also where crossing the annular conductor; lightning arresters for outside electric lines and also for the lowest points of the building wiring (to remove

static charges); complete interconnection and grounding of all metal objects in the interior.

This paper has been prepared for the purpose of stimulating discussion and further investigation along similar lines, rather than for the advancement of any new theories. Others, for example, Sir Oliver Lodge and Prof. Elihu Thomson, have already pointed out that lightning discharges may be non-oscillatory and yet produce all the effects that seem to have led to the assumption that they are oscillatory in character. As for the laboratory investigations, both on primary and induced effects, it is recognized that these could have resulted in further and more certain conclusions had they been pursued with the aid of larger apparatus—such as is probably readily available to others, and to these the hope is expressed that they may become further interested in the investigation both of lightning discharges and of sparks produced artifically in the laboratory, as well as their interrelation with its bearing on the protection of buildings.

DISCUSSION ON "SOME INVESTIGATIONS ON LIGHTNING PROTECTION FOR BUILDINGS" (DEBLOIS), WASHINGTON, D. C., APRIL 24, 1914.

E. E. F. Creighton: There has been very little work done on the direct study of cloud lightning, and therefore this paper may be considered as a turning point. There is no committee at the present time of the American Institute of Electrical Engineers or of the National Electric Light Association which will give this subject the study that is needed. Perhaps the problem is important enough to receive the attention of the Bureau of Standards, and it would be an excellent one for that bureau to take up. It requires not only an organization of trained laboratory men, but also men who can develop instruments as they are required by the conditions that become apparent.

One very important point that has been discussed many times is the natural frequency of the lightning stroke. A great many of the great scientists of the world have discussed it—I think Professor Thomson has given a number of discussions on it, and also Dr. Steinmetz, and the matter is still held in abeyance. I do not think that the work done with the oscillograph can prove either that the frequencies are high or are low, because the oscillograph will not respond to these high frequencies, although it will respond to the summation of them. I have obtained instances of summation in the laboratory with five million cycles per second. This discharge through the oscillograph gives a deflection. Of course, what was produced in the oscillograph was the summation of the oscillations, giving the resultant quantity of electricity that had passed through the bifilar vibrator. Theoretically, I think there is in some cases a high frequency, and practically, types of lightning arresters which are sensitive to high frequencies and not very sensitive to impulses, respond by discharging, showing that there is at times a high frequency in the lightning.

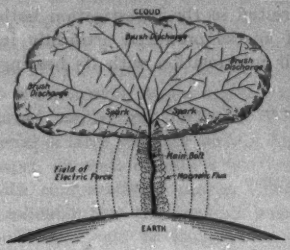


FIG. 1

Theoretical analysis of the cloud conditions, will, perhaps, illustrate what part of the discharge can oscillate and what part of the discharge cannot. Assuming that the electricity is freed at different points in the cloud, as shown in Fig. 1 herewith, there will be a brush discharge from different parts of the cloud toward one centralized point A that is failing, and as it approaches that centralized point there will be formed vapors of sufficient in-

tensity to be called spark discharge. Up in the outermost parts of the cloud the electricity is drawn through high resistance, and all the laboratory experiments show that this resistance is above the critical value which will allow oscillations. The conditions of high resistance exist even in those parts where the blue brush discharge is just turned to a definite bright spark discharge. But somewhere just above the point A, around the upper part of the main bolt of lightning, the resistance becomes very low. From this region down to earth there is a good conductor to transmit current, which is surrounded by magnetic energy, indicated in the sketch by rings around the main bolt. There is also a high voltage from end to end of the main bolt which gives electrostatic energy. These three conditions, electromagnetic energy, electrostatic energy and low resistance, will naturally produce an oscillation. Therefore I think there is an oscillation in the main part of the discharge path, but the discharge in the rest of the cloud could not possibly oscillate.

George R. Olshausen: I congratulate Mr. DeBlois on being successful in getting any registrations whatever with the oscillograph in the short period of time of twenty minutes in which this work was done. You must remember that we do not know when the lightning is coming, where it is coming, and when you bear in mind that we only have twenty minutes in the whole season to work in, I think it is very remarkable that Mr. DeBlois secured any results at all. He seems to think that these registrations cannot be the so-called related charges. Professor B. Walter, of Hamburg, first took pictures by means of a moving camera, and showed that, in general, the lightning stroke consists of a great number of parts, showing that there is a so-called predischarge which breaks down the air, first going part of the way, and then proceeding a little further, and finally a complete flash is made. This first flash usually heats up the air and makes it more conducting than before. After the first discharge there is usually a period of rest, and then there may be a gradual leaking of electricity along this heated part, which might make a continuous current for quite a long time, and then there may be a series of intervals and discharges, and finally there may be a closing flash something like the residual discharge of the condenser.

As to the period of the discharge, something can be said in both directions, that is, for the unidirectional discharge and also for the associated discharge. The experiments made by Pockels in determining the current of a stroke of lightning, by means of the magnetizing effect on prisms obtained from the mineral base salt, seemed to indicate that the flash is unidirectional, and occasionally that they were not magnetized at all, and in that case we may have been dealing with an oscillatory flash. Ende (*Electrotechnische Zeitschrift*) has made some calculations by means of the Maxwell equations on the frequency of a flash, and he comes to the conclusion that its probable frequency is some-

thing like 8000 oscillations per second. However, a great many assumptions are made in this calculation. One assumption, for instance, is in regard to the self-induction of such a flash. What is the self-induction of a circuit which is not closed? Hertz says there is no such thing as self-induction of a straight rod. Our ideas of self-induction, when applied to closed circuits, are not very well defined.

A. G. Webster: As to the conclusions in the paper, I agree with what has been said by the two preceding speakers. There is no doubt that Fig. 2 shows an oscillation there, but it has not been proved that there are any high-frequency oscillations. Whether there are any such, I do not know, and I do not suppose anybody else does, although Professor Thomson, in talking with me recently, admitted that he did not believe there were any high-frequency oscillations.

All that Dr. Olshausen said about the complication of the phenomenon is absolutely true. As Dr. Olshausen has said of self-inductance, I believe there is self-inductance here. But what is it? It is much worse to calculate than the reluctance of a solenoid. Everybody knows that, who has examined, experimentally, sparks in revolving mirrors. I have examined them for a good many years, and I believe, perhaps, I was the first to show the oscillatory character of such discharges in a lecture which I delivered in the Lowell Institute at Boston seventeen years ago. There is always at the start of the discharge something that does not come as regularly as the rest, that is, there is a breaking away which heats the air, ionizes it, and after that come the regular flashes—these come pretty regularly after that.

In this connection I think of a commonplace phenomenon which Professor Thomson will corroborate or disprove, because there is no one who makes more daily observations from just looking out and looking around than he does. I believe that it is very common for barns with hay in them to be struck by lightning, and I suppose the reason is that there is somewhere an upward current of hot air. As has been said, these lightning strokes have been blown about. In Fig. 2 of the paper, in the upper part of the photograph you see the discharge is not straight and in the lower part it has apparently been blown about very violently. We have been told to look out for current when it strikes. You cannot tell when a lightning stroke is coming, and you cannot dodge a lightning stroke. There are places where hot currents of air seem to make good paths for the lightning. Whether the heat resistance is above or below, it is hard to tell. If it is above, it will not be oscillatory. You engineers know what the resistance of a long arc is, and I am pretty sure that when the arc is gone, the resistance goes down very much, indeed.

As has been said, the whole thing is a good deal like a Hertzian oscillator, only the cloud is spread out some times for miles, and as you watch it you do not get as good observation as in revolving

machinery, but you get something. What Dr. Olshausen has said is true, it breaks away all over, and whether that is hard to see clearly or not, I do not know.

As I said; this photograph shows an oscillation. There is one thing which is evident, if there had been a different potential between the cloud and earth, or the free cloud, there would not be a lightning stroke. There must be a condenser, and in order to have a stroke it might empty itself out. You speak of the residual discharge in a Leyden jar, but you seldom find discharge going up the other way. The oscillograph will certainly show a current, if it does not burn out, or if something else does not happen to it.

Elihu Thomson: The results Mr. DeBlois has shown are, in a large measure, explanatory of what has been my impression for years, in fact, as long as I can remember having any thought or dealings with lightning or lightning protection. While it may be true that within the path of the discharge there may be oscillatory portions, I think the main phenomenon is that of a continuous current.

I arrived at that conclusion early in my investigations in this wise: I have been in telegraph offices when lightning struck at some place nearby, and have been near a telephone when lightning also was nearby, and I found that the relays went click, click, click. They acted as if they had received a direct current—no high frequency, pure and simple, would have induced such an effect in the relays; it would instead have jumped the relay and sparked across the terminals.

So, also, everybody knows that during a thunderstorm a telephone bell is frequently rung—which means that a current went through the numerous turns of the electromagnet. That could not be induced by high frequency, it was induced by a steep wave front and not obliterated by the reversal of the phase of the wave, as would be the case with high-frequency effect.

I quite agree with Mr. Creighton in the assumption that there may be in the length of a long discharge to earth some parts where there is oscillation, but if I were to picture the effect, as it occurs to me, it would be about as follows:

I will first make the statement that I do not think it is quite the thing to consider a cloud as a charged conductor. That statement I have made many times. It is not a conductor. It is a very poor conductor—it is a mass of fog. You cannot locate charges on it as you can on a tinfoil condenser. The cloud has plus or minus charges all through. They tend, naturally, to approach the earth, which has the opposite charge.

Somewhere in this system, perhaps where the cloud dips down a little, over an object on the earth's surface a little higher than the rest, there is a beginning of the breakdown. No doubt it begins as accumulation of a free charge and rapidly develops into a discharge. It discharges the lower part of the cloud, and as that begins to discharge, the rest of the cloud starts to feed into it, the cloud path ramifying like tree branches in all directions.

Many photographs, even the photographs shown on the screen a short time ago, show two other discharges in the same field, fine discharges, leading down this way and that; what are they? They are the perspective projection of the more or less horizontal discharges miles away in the cloud and feeding the main discharge.

I have one particular picture, which I wish I had brought along with me, which shows a tremendous discharge in the middle distance, and then down to the far horizon of the picture, from this main discharge point, there are branching discharges which apparently lead away in all directions. It is like a great tree, the branches feeding into one massive spark. Now, if that feeding distance is five or even ten miles, as it may easily be, then, the limit of rate of breakdown being the velocity of light, high frequency is forbidden. I mean by this that if the energy is to oscillate through the whole length of such a long path of discharge it cannot do so at a high frequency, for during a quarter wave it will need to travel say five miles. The highest possible speed is light velocity, and even at that speed the period is not above 9000 per second.

On one occasion I heard a thunder clap which had a true musical sound, like the sound of a bell. I was convinced in that case that it must have been a discharge of relatively low frequency, I should say not more than three hundred or four hundred vibrations per second.

I have been asked to state why it is that barns are struck by lightning so often, especially when they have moist hay, etc., in them. They are struck pretty often when they have no hay in them, and I do not know that the moist hay has much to do with it. If they are struck by lightning while the hay is in them, they may be burned; if they are struck by lightning when there is no hay in them, they may not be burned. Of course, the combustible material takes fire very readily. That may be the difference. But let us ask—why is the barn struck primarily? Because it has one of the best grounds that can exist. The ammonia salts, the drainage from the cows and horses, soaks into the earth, and that forms a direct connection to the earth. That is why the barn is struck. Why is a barn equipped with lightning rods, which take the charge directly to the ground, struck by lightning and destroyed? Because no conducting ground outside the barn can be compared to the splendid ground which exists inside the barn. We would naturally expect the lightning to go to the best conductor, the best ground on the premises. Let me emphasize this. It will take the best ground on the premises, and that is within the barn. The moral of it is that lightning rods should be anchored where the *best ground is obtainable, in all cases*—something which is quite generally forgotten in providing lightning protection.

I have very little confidence in investigations in lightning phenomena made with small apparatus like the ordinary static machine. In the first place, you cannot imitate a cloud, no mat-

ter how you try, you cannot get any representation of it, by any machine. Among others, Sir Oliver Lodge made some investigations in that way. He used a copper sheet to represent a cloud—mounted below it little rods of copper, iron, and different substances, and then concluded, because he got the snappiest spark with the copper, that copper was the worst material of which to make a lightning rod, and that iron was a very much better material. When we go back to the figures I gave before, and the photographs of lightning discharge I have considered which show a tremendous stroke of lightning falling on a house—the house is about 20 feet high—the spark runs up to the clouds, and ramifies in it miles away, we ask—What influence can a rod of copper or iron have on the character of that discharge; a few feet of rod on a few miles of spark? What is his conclusion worth, where the spark is miles long, and the lightning conductor is an almost infinitesimal part of the path?

In regard to the residual discharge of the Leyden jar, we have taken that to mean that a part of the charge soaked into the glass, and that when we discharged the jar there was need of time for the glass to deliver the soaked charge to the coat of tinfoil. This leaves a slight charge which can give a residual discharge. It depends on a known property of glass, called soakage. We have nothing of that kind in the case of lightning, necessarily.

It is very easy to understand, it seems to me, why with lightning we should observe repeated discharges down the same path. The first discharge establishes a fairly good conductor to ground and some other charged portion of the cloud, more distant, now finds it easy; as it were, to take up that path and discharge; but this will not be instantaneous. It takes some time, according to the velocity of light, for stresses to arrange themselves for the second discharge. Thus there is a slight interval before the charge reaches its full amount and takes the path opened by the first discharge.

W. J. Humphreys: There is one point I want to call attention to. I will not go into a discussion of the entire paper, though it is very interesting to me. This subject has interested me very much in the last three months. The point I have in mind covers one thing which has not been mentioned, as a possible evidence against the oscillating nature of the discharge. We will often find in a discharge of some kind or other, going down, where there are short breaks, secondary discharges going off from it in branches, just as we have in the case of the ordinary discharge between the terminals of an ordinary alternating-current machine. But when we examine these with a rotating camera we never find that they come back in that way, they are always going off in the same direction, whatever direction it may happen to be. You do not find succeeding discharges going in the opposite direction, which we might possibly expect—that we would have a discharge going first in one direction and then in the opposite

direction. In the case of the succeeding discharges, we will find in some few cases—in exceedingly few cases, but in some cases—that there will be a feeble discharge passing off in the same direction. Sometimes it may be that there go out directly a dozen branches in all. This shows, since the branching may occur a second and third time, that if you had them oscillating you could probably get them going that way, as well as this way, but you do not find that.

In the case of the lantern slides shown a short while ago, there is one particular point in regard to them that Dr. Olshausen understands possibly better than I do, but I have had occasion to study exactly the same phenomena. I feel convinced, with these two discharges that come down, one apparently being instantaneous and done with, and the other one that repeats itself, that the two start out in identically the same manner, and in the subsequent case the main branches break off and divide.

George R. Olshausen: I would like to say that these two discharges are entirely separate and the time between is 0.129 of a second. They have been calculated. They are not connected, they do not run down the same path. The time is calculated by taking a photograph with the stationary camera, and at the same time with the moving camera, and it is easy enough to calculate the time between the two flashes.

Professor Walter, of Hamburg, has photographed sparks having a frequency of 300,000 per second. The trouble with our lightning photography is that we have a flash which has a duration of a very short period of time, combined with high frequency, and in trying to photograph that we must be sure that the first registration is not wiped out by the successive flashes which may take place. We therefore must make our registration on a spiral, or something of that kind, so that when we think we have any evidence of oscillations they may not be wiped out by the succeeding flashes.

Trygve D. Yensen: A few years ago I became interested in an investigation conducted by Professor E. J. Berg of the University of Illinois to determine the character of lightning discharges. During this investigation a few preliminary experiments were conducted in the laboratory by discharging sparks from a static machine and Leyden jars through a circuit containing a resistance, an inductance and a condenser in series, each one being shunted by a spark gap. The spark gaps were adjusted, until the distances were found that corresponded to the voltages across the resistance, inductance and condenser respectively. The experiments showed that the voltage across the inductance was practically zero, while that across the condenser was beyond the limit of the apparatus. This result, after making numerical calculations, pointed towards a unidirectional discharge. Although these experiments were not conducted with refined apparatus, they confirm the results obtained by Mr. DeBlois.

The main part of the investigation was carried out with apparatus similar to the ones described above, but placed upon six separate poles, 40 ft. high, distributed 100 ft. apart in an open field. The recording apparatus were connected in series with lightning rods, thoroughly grounded and extending above the tops of the poles. This outfit has now been in the field for four years, and although lightning storms have been quite frequent, the only record obtained has been of minute discharges across the condensers. Not a single direct discharge to the rods has taken place. At one time a barn 2000 ft. away was struck by lightning and burned down, but even then the record obtained was only a small discharge across the condenser. Similar results were obtained from an outfit erected near my residence. Here the lightning rod was placed in a tall tree, extending 80 ft. above ground.

Although our experiences have been mostly negative, they may be of some value when considered in connection with the important results obtained by Mr. DeBlois.

L. A. De Blois (by letter): In preparing this paper the writer made no assertion that the current in all lightning discharges was unidirectional, but pointed merely to the fact that the comparatively few records obtained on the oscillograph seem to indicate that the currents in the particular discharges that occurred at that time were in the main unidirectional.

Mr. Creighton casts some doubt on the action of the oscillograph under high frequencies. It so happens that some special investigations were made by myself along these particular lines. I found that the oscillograph would respond ballistically to a Leyden jar discharge estimated at 3,000,000 cycles when passed across a spark gap into the instrument. On further investigation, however, it was perceived that the estimate of the frequency was entirely wrong on account of failure to take into consideration the resistance of the spark gap itself. When the length of this was reduced so that its resistance became inconsiderable and the discharge current actually approached the estimated frequency of 3,000,000, the oscillograph ceased to respond, except by having its elements burned out without deflection. When tested at somewhat lower frequencies its working limit, so far as response to the oscillations was concerned, lay somewhere above 80,000, at which point it became impossible to obtain a record on the photographic film—the limit being fixed by the sensitiveness of the latter to a rapidly moving spot of light of the intensity available. Since the summation of a high-frequency oscillating wave should be nearly zero, I cannot see why we should expect the oscillograph to act otherwise.

Professor Thomson has cited a number of very interesting points that have led him towards the unidirectional theory of discharge, and to these I can add one which seems to somewhat oppose Mr. Creighton's suggestion that oscillations could occur

more readily in the part of the discharge from clouds to earth, than in the ramified discharges among the clouds. If a high-resistance telephone receiver is connected directly between a wireless aerial and the earth, without other inductance or capacity, it will be found that discharges between the clouds produce a rough crackling sound, while a discharge from clouds to earth produces a sharp clicking or series of clicks at intervals suggestive of the "related" discharges of Professor B. Walter, and which correspond, so far as can be distinguished by eye, to the pulsations in the discharge itself. Actually all these latter discharges, that is, the sharp clicks, are preceded by more or less prolonged noises of the former variety, which, I imagine, indicate the breaking down of the air in the body of clouds—in fact, the "progressive breakdown" described by Dr. Steinmetz. For the same reason I ascribe the sharp clicks to the disruption of the atmosphere between earth and clouds, the sounds of which certainly do not suggest the existence of high or even moderate frequencies.

I think almost all of us have become so attached to the high-frequency theory of lightning discharges that it is very difficult to conceive of anything else occurring. Perhaps, also, some of the discharges in the laboratory which we have heretofore considered high frequency are after all only unidirectional discharges of exceedingly steep wave-front. After all, there is very little difference between the two, since the rapid rise of current from zero to maximum in the latter type of discharge is practically equivalent to the first quarter period of an oscillation, if its frequency is sufficiently high. Over and beyond this, the effects produced by the two will be practically identical except where resonance conditions are involved.

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SOME SIMPLE EXAMPLES OF TRANSMISSION LINE SURGES

BY W. S. FRANKLIN

ABSTRACT OF PAPER

The paper treats of the true wave phenomena which take place on a transmission line when switches are opened and closed or when a circuit breaker operates. These phenomena are practically the same in alternating- and direct-current systems for transmission lines up to say 150 or 200 mi. (240 or 320 km.) in length, and therefore the surges which are described in the paper are the surges which take place when a steady voltage is connected to the line or when the line is disconnected with a steady current flowing in it.

The details of line surging which takes place under such conditions are most easily described in terms of what may be called the "ribbon wave", and the first part of the paper is devoted to a discussion of the ribbon wave. Then a number of practical examples are described in detail.

THE LINE surges which are described in this paper are so rapid on transmission lines of moderate length that all the details as described take place during a very small fraction of a second and any change of 60-cycle voltage or current is negligible during the very short interval of time involved. Therefore the effects which are described occur in substantially the same way in direct-current systems and in alternating-current systems.

The effects of line resistance and leakage on a line surge are extremely complicated; indeed, these effects cannot be expressed in finite algebraic terms. Usually, however, line resistance and leakage are small, and therefore a line surge on an actual transmission line approximates in its early stages the character it would have if line resistance and leakage were zero. Line resistance and leakage are assumed to be zero throughout the following discussion.

The complete solution of the differential equation of wave motion on a transmission line is involved in or expressed by the simple idea of travel[1]; and the use of this idea is exactly equiva-

1. This is by no means the case when line losses are taken into account.

lent to the use of the general analytical solution of the differential equation of wave motion; namely:

$$y = f(x - vt) + F(x + vt) \tag{1}$$

To solve a particular problem, the two unknown functions f and F must be determined so as to satisfy the given conditions which exist over the line at the beginning ($t = 0$), and so as to satisfy the conditions which are continuously impressed on the

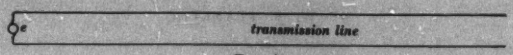

FIG. 1

line at its ends. In this connection it must be remembered that either of the functions f or F may be zero or a constant, and it must also be remembered that any number of separate solutions of the differential equation of wave motion can be superposed upon each other to get a desired solution. Thus the heavy dotted line AB in Fig. 17 represents a constant initial distribution of current over the transmission line; and when the end of the line in Fig. 17 is opened, a long-drawn-out wave shoots out from the

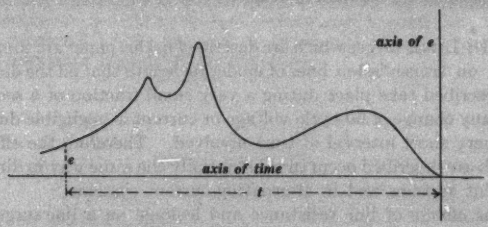

FIG. 2—SHOWING VOLTAGE e OF FIG. 1 AS A FUNCTION OF THE TIME

opened end, and is repeatedly reflected at A and B. The superposition of the initial current and any number of successive laps of the long-drawn-out wave gives the desired solution of the differential equation of wave motion.

An interesting example is to consider the effect produced when a variable voltage e is applied to one end of an indefinitely long transmission line as shown in Fig. 1. The curve in Fig. 2 expresses e as a known function of the time, and the wave that shoots out from e in Fig. 1 is shown by the curve in Fig. 3. The

curve in Fig. 3 evidently gives the correct solution, because in the first place the idea of travel satisfies equation (1), that is to say, the idea of travel satisfies the differential equation of wave motion; and in the second place the value of e in Fig. 3 is equal to the value of e in Fig. 2 at all times, that is to say, the wave in

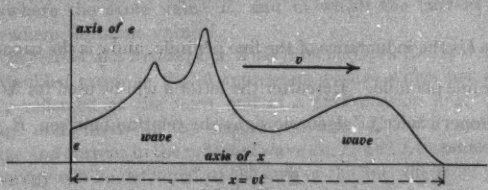

FIG. 3—SHOWING SHAPE OF WAVE WHICH SHOOTS OUT FROM e IN FIG. 1

Fig. 3 satisfies the condition which is continuously impressed upon the line at the end e in Fig. 1.

A clear idea of the essential details of an electromagnetic wave on a transmission line may be obtained with the help of Fig. 4. The curve $W\,W$ in the lower part of the figure represents the shape of the wave, that is to say, the ordinate y represents the current

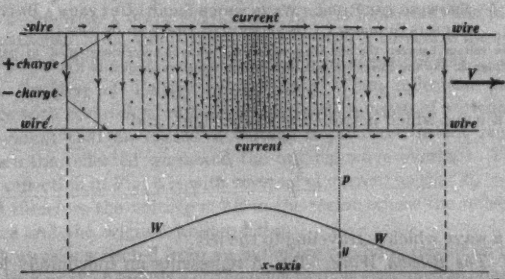

FIG. 4—SHOWING AN ELECTROMAGNETIC WAVE ON A TRANSMISSION LINE

in the wires at the point p or the voltage between the wires at the point p, and of course the curve $W\,W$ may be of any shape whatever. The dots in Fig. 4 represent the magnetic lines of force which are perpendicular to the plane of the paper.

1. *Relation between Current and Voltage in a Pure Wave.* The differential equation of wave motion on a transmission line

(when line losses are negligible) involves a fixed relation between voltage and current on a line in connection with a traveling wave.

This relation is

$$\frac{E}{I} = \pm\sqrt{\frac{l}{c}} \tag{2}$$

where l is the inductance of the line per mile, and c is the capacity of the line per mile. Hereafter the letter a will be used for $\sqrt{\frac{l}{c}}$. By proper choice of algebraic signs the relation between E and I becomes

$$\frac{E}{I} = +a \tag{3}$$

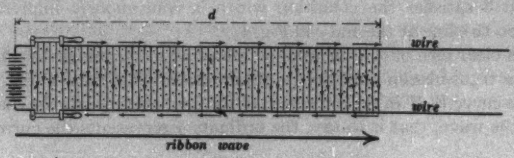

FIG. 5—SHOWING THE RIBBON WAVE WHICH SHOOTS OUT FROM A BATTERY WHICH IS SUDDENLY CONNECTED TO THE END OF THE LINE

The voltage between the line wires within the wave is everywhere equal to battery voltage E, and the current in each wire within the wave is equal to E/a.

for a wave which is traveling to the right, and

$$\frac{E}{I} = -a \tag{4}$$

for a wave which is traveling to the left.

2. *The Ribbon Wave.* Fig. 5 represents an indefinitely long transmission line to which a battery has been suddenly connected. Assuming battery resistance to be negligible, the result is that battery voltage E and the corresponding current I ($= E/a$) is established in the line by a long-drawn-out wave which shoots out from the battery. This is a simple example of the general case which is shown in Figs. 2 and 3. If the distance d in Fig. 5 is 18.6 mi. (29.93 km.), then Fig. 5 represents the state of affairs 0.0001 of a second after the closing of the switch. The long-

drawn-out wave in Fig. 5 may be completely represented by the heavy arrow at the bottom of the figure, if it be remembered that the arrow represents the existence of a certain voltage E and the corresponding current I at each point along the line. In most of what follows we have to do with what are called *rectangular waves*. A rectangular wave is a wave in which the voltage has everywhere the same value E, and in which the current has everywhere the same value I.

3. *Reflection of a Rectangular Wave from the Open End of a Line.* The doubled arrow in Fig. 6 represents a wave which has been partly reflected at the open end of a transmission line. The voltage and current in the original wave are E and I, and the voltage and current in the reflected wave are E_r and I_r respectively. No energy can be delivered to the end of the line, therefore voltage and current have the same values in the reflected wave as in the original wave. The direction of progression of the reflected wave being the reverse of that of the original wave requires that either voltage or current be reversed, but not both. The total voltage at the end of the line $E+E_r$ can have any value whatever, but the total current $I+I_r$ must be zero. Therefore $I_r=-I$ and $E_r=E$. *Reflection takes place with reversal of current at the open end of a transmission line.*

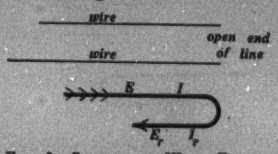

FIG. 6—SHOWING A WAVE PARTLY REFLECTED FROM THE OPENED END OF A LINE

4. *Doubling of Voltage by Reflection.* When reflection takes place with reversal of current and without reversal of voltage, it is evident that an excessive voltage is produced in the region where the reflected wave and the original wave overlap. Thus the reflection in Fig. 6 is with reversal of current so that $E_r = E$, and therefore the voltage is $2E$ in the region where the reflected wave and the original wave overlap.

A wave is reflected from an inductive receiving circuit so that $E_r = E$ at the beginning of the reflection, as explained in connection with Fig. 9. Therefore a doubled voltage is produced in this case.

This rise of voltage due to reflection is important. Thus a wave may enter an underground cable with insufficient voltage to damage the cable, but if the other end of the cable is open, or if inductive apparatus is connected across the other end of the cable, then a doubled voltage will be produced when the wave

is reflected from the other end of the cable. If such a cable must not be subjected to more than 2000 volts, a spark-gap arrester breaking down at 1000 volts must protect the cable where it connects to an air line.

5. *Reflection of a Rectangular Wave from the Closed End of a Line.* The double arrow in Fig. 7 represents a wave which has been partly reflected from the short-circuited end of a transmission line. No energy can be delivered to the end of the line, therefore voltage and current have the same values in the reflected wave as in the original wave. The direction of progression of the reflected wave is opposite to the direction of progression of the original wave; therefore either voltage or current must be reversed, but not both. The total current at the end of the line $I + I_r$ can have any value whatever, but the total voltage $E + E_r$ must be zero.

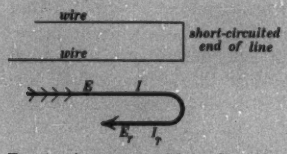

FIG. 7—SHOWING A WAVE PARTLY REFLECTED FROM THE SHORT-CIRCUITED END OF A LINE

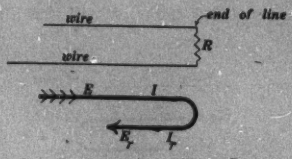

FIG. 8—SHOWING A WAVE PARTLY REFLECTED FROM A NON-INDUCTIVE RECEIVING CIRCUIT OF RESISTANCE R

Therefore $E_r = -E$ and $I_r = I$.

Reflection takes place with reversal of voltage at the closed end of a transmission line.

6. *Reflection of a Rectangular Wave from a Non-Inductive Circuit connected across the End of a Line.* The doubled arrow in Fig. 8 represents a wave partly reflected from a non-inductive circuit of which the resistance is R. The ratio of voltage to current must be the same in the original and in the reflected wave, except for reversal of sign, therefore

$$\frac{E}{I} = +a \tag{5}$$

and

$$\frac{E_r}{I_r} = -a \tag{6}$$

These two equations define the original wave and the reflected wave as pure waves, the only kind which can exist if line resistance and line leakage are negligible. The total current at the end of the line in Fig. 8 is $I + I_r$, and this current flows through the receiving circuit. The total voltage across the end of the line in Fig. 8 is $E + E_r$, and this voltage acts across the receiving circuit. Therefore, since the receiving circuit is non-inductive we have

$$I + I_r = \frac{E + E_r}{R} \tag{7}$$

The original wave is supposed to be given, and the ratio E/I necessarily satisfies equation (**5**). Equations (**6**) and (**7**) contain, therefore, the two unknown quantities, E_r and I_r, and solving for these quantities we get

$$E_r = E\left(\frac{R - a}{R + a}\right) \tag{8}$$

and

$$I_r = I\left(\frac{a - R}{a + R}\right) \tag{9}$$

When $R = a$ and there is no reflected wave at all, the entire original wave is swallowed up, as it were, by the receiving circuit.

When R is greater than a, there is partial reflection with reversal of current; thus when $R = 3\,a$, we get $E_r = \frac{1}{2}\,E$, and $I_r = -\frac{1}{2}\,I$.

When R is less than a, there is partial reflection with reversal of voltage; thus when $R = \frac{1}{3}\,a$, we get $E_r = -\frac{1}{2}\,E$, and $I_r = \frac{1}{2}\,I$.

7. *Reflection of a Ribbon Wave from an Inductive Receiving Circuit.*[2] The solution of this problem is completely represented in Fig. 9 for the case in which $R = \frac{1}{3}\,a$. At the instant that the head of the ribbon wave strikes the receiving circuit the reflection is complete with reversal of current ($E_r = E$ and $I_r = -I$), because an appreciable current cannot be instantaneously established in the inductive receiving circuit. Current is, however, slowly established in the receiving circuit, and the reflected wave becomes weaker and weaker, passes through zero, and then grows stronger and stronger again, until finally we get that particular degree of steady reflection with reversal of voltage ($E_r = -\frac{1}{2}\,E$,

2. The analytical solution of this problem is given in Franklin's "Electric Waves," pages 99–101.

and $I_r = \frac{1}{2} I$) which depends upon R alone. The curves cc in Fig. 9 are exponential curves, and the value of the exponent is $-\frac{R+a}{L} \cdot t$, where t is the abscissa expressed in seconds.

8. *Transmission Line Surges which Follow the Switching on of a Generator.* A generator of negligible resistance and reactance is suddenly switched on to a line, and a ribbon wave of generator

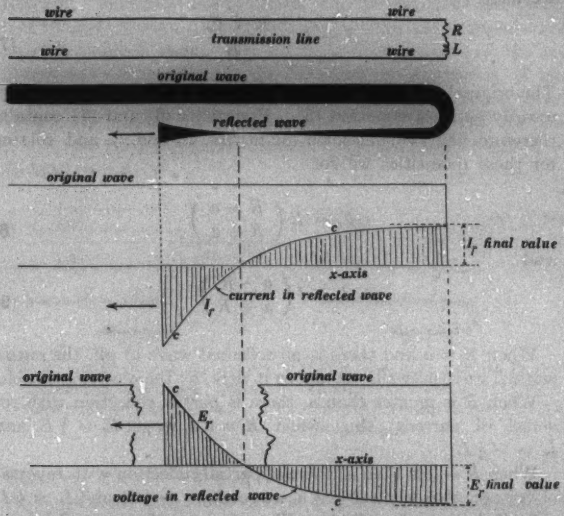

FIG. 9—SHOWING REFLECTION OF A RIBBON WAVE FROM A RECEIVING CIRCUIT OF RESISTANCE R AND INDUCTANCE L, WHEN $R = \frac{1}{2} a$

voltage and corresponding current $\left(\frac{E}{I} = a\right)$ shoots out along the line. Assuming line resistance and leakage to be negligible, this ribbon wave is reflected back and forth as indicated in Fig. 10 or Fig. 11, and by adding together the voltages and currents in the successive laps, a precise knowledge of the distribution of current and voltage over the line at any instant may be obtained. Thus, after a thousandth of a second, the total travel would be 186 mi. (300 km.), and by dividing this travel by the length of the line we get the number of laps of the ribbon wave, with a certain

fraction of the next lap. By carefully reckoning up successive laps in this way complete curves can be easily plotted, showing the voltage across the line and the current in the line at any point of the line as functions of elapsed times. The ampere-time curves in Figs. 10 and 11 were obtained in this way.

The ribbon wave is reflected from the distant end of the line with reversal of current or voltage according as the distant end of the line is open or closed; and the character of the reflection of the ribbon wave at the battery end of the line is determined by

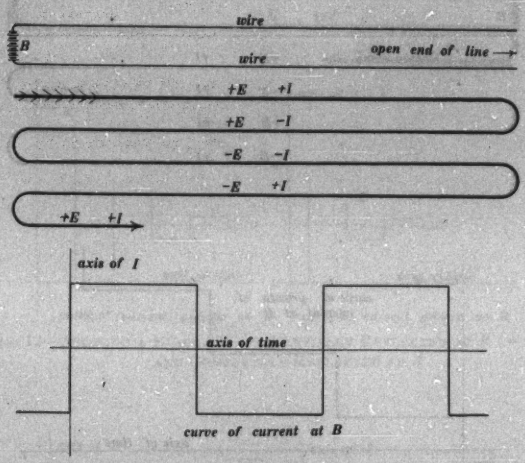

FIG. 10—SHOWING WAVE WHICH SHOOTS OUT FROM A SUDDENLY CONNECTED BATTERY, WAVE BEING REPEATEDLY REFLECTED AT BOTH ENDS OF THE LINE

the condition that the total voltage across the battery end of the line must always be equal to battery voltage.

Fig. 12 shows what happens when a generator of negligible resistance and inductance is switched on to a transmission line, a non-inductive receiving circuit being connected across the other end of the line. Fig. 12 shows the case in which $R = 3a$. In this case voltage and current are each reduced to half, and current is reversed by reflection from R. The character of the reflection from the battery end B is determined by the same condition as in

Figs. 10 and 11, and this reflection is complete, battery resistance being negligible.

Fig. 13 shows the growth of current at B in Fig. 12 and Fig. 14 shows the growth of current at R in Fig. 12 for the case in which $R = \frac{1}{3}a$. In this case voltage and current are each reduced to half, and voltage is reversed by reflection from R.

9. *Reflection at a Place where the Line Constants Change.* An

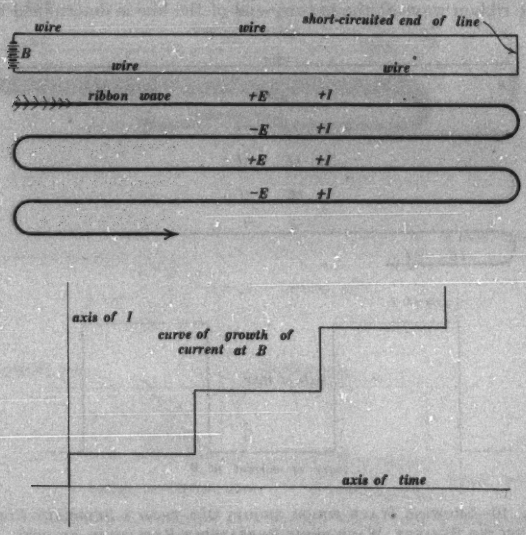

FIG. 11—SAME AS FIG. 10 EXCEPT THAT THE DISTANT END OF THE LINE IS SHORT-CIRCUITED

important case to consider is where an air line connects with an underground cable as shown in Fig. 15. A rectangular wave with voltage E and current I is partly turned back or reflected from the end of the cable, and partly transmitted into the cable. It is required to find the voltage and current values E_r and I_r in the reflected wave, and the voltage and current values E_t and I_t in the transmitted wave.

There are two expressions for the total voltage across the line

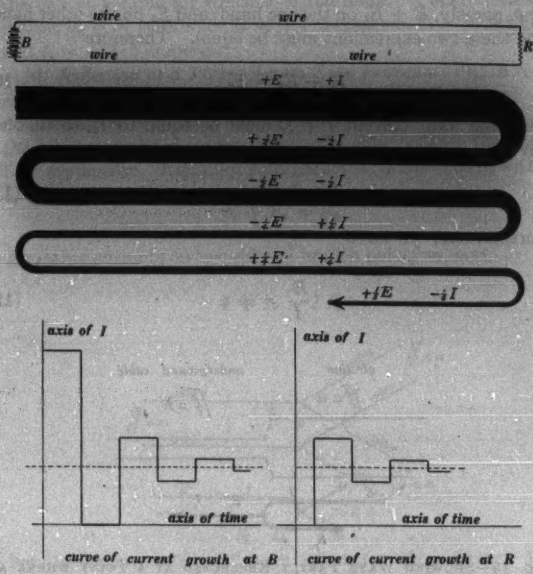

FIG. 12—SHOWING A RIBBON WAVE PARTIALLY REFLECTED AT R ($= 3a$) AND COMPLETELY REFLECTED AT B

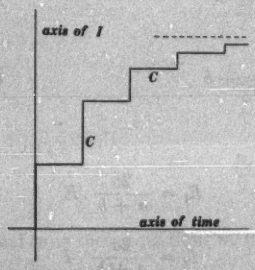

FIG. 13—SHOWING GROWTH OF CURRENT AT B IN FIG. 12, WHEN $R = \frac{1}{3}a$

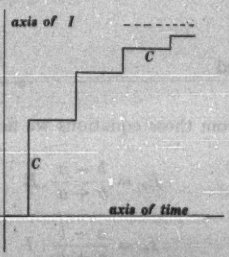

FIG. 14—SHOWING GROWTH OF CURRENT AT R IN FIG. 12, WHEN $R = \frac{1}{3}a$

at p, namely, $E + E_r$ on the one hand, and E_t on the other hand, and these two expressions must be equal. Therefore

$$E + E_r = E_t \tag{10}$$

Also, the total current $I + I_r$ must be equal to I_t, so that we have

$$I + I_r = I_t \tag{11}$$

Furthermore, we have

$$\frac{E}{I} = +a \tag{12}$$

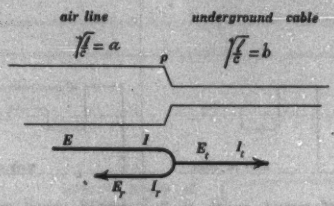

FIG. 15—SHOWING WAVE PARTLY REFLECTED AT A POINT WHERE AN AIR LINE CONNECTS WITH AN UNDERGROUND CABLE

$$\frac{E_r}{E_r} = -a \tag{13}$$

and

$$\frac{E_t}{I_t} = +b \tag{14}$$

From these equations we find

$$E_r = \frac{b-a}{b+a} \cdot E \qquad E_t = \frac{2b}{a+b} \cdot E$$

$$I_r = \frac{a-b}{a+b} \cdot I \qquad I_t = \frac{2a}{a+b} \cdot I$$

For example, a wave in which $E = 1412$ volts and $I = 2$ amperes ($a = 706$ ohms) travels along an air line, and comes to

the end of a cable for which $b = 100$ ohms. Under these conditions $E_r = -1063$ volts, $I_r = +1.5$ amperes, $E_t = +349$ volts, and $I_t = +3.5$ amperes.

10. *Reflection at a Place where a Line Branches.* Fig. 16 represents a place where a line branches into two similar lines. The doubled arrow represents a partly reflected rectangular wave, and the two transmitted waves are exactly alike because the branch lines are similar. Equating voltages across branch point, we have

$$E + E_r = E_t \tag{15}$$

Equating currents on two sides of branch point, we have

$$I + I_r = 2\,I_t \tag{16}$$

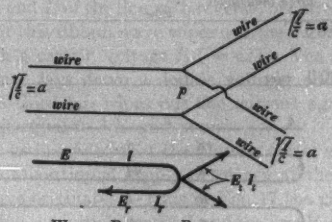

FIG. 16—SHOWING WAVE PARTLY REFLECTED AT A BRANCH POINT OF AN AIR LINE

Also, for each individual wave we have

$$\frac{E}{I} = +a \tag{17}$$

$$\frac{E_r}{I_r} = -a \tag{18}$$

$$\frac{E_t}{I_t} = +a \tag{19}$$

and from these equations we find

$$E_r = -\tfrac{1}{3}\,E \text{ and } I_r = +\tfrac{1}{3}\,I$$

and $$E_t = \tfrac{2}{3}\,E \text{ and } I_t = \tfrac{2}{3}\,I$$

That is, the reflected wave represents 1/9 of the energy of the original wave, and each transmitted wave represents 4/9 of the energy of the original wave.

11. *Transmission Line Surges which are Produced when a Circuit Breaker Opens.* When a circuit breaker opens, the arc which is formed persists for a very long time, relatively speaking, and the open gap in the circuit is filled with a fairly good conducting material which slowly loses its conductivity. It is about as nearly impossible to produce characteristic line surges by opening a circuit breaker as it would be to set up an abrupt water wave in a canal by allowing a cubic mile of soft mud to flow into the canal prism to stop a troublesome flow of water in the canal; and yet the moon, as a 60-cycle generator (60 cycles per month!)

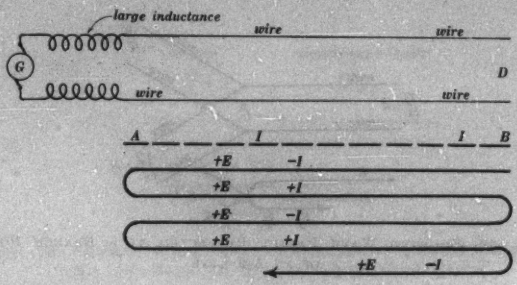

FIG. 17

The dotted line AB represents the initial current in the transmission line. The long heavy arrow represents the ribbon wave which comes from D after the line at D is opened.

might produce a troublesome tidal wash in a large estuary while the attempt was being made to "open-circuit" the estuary in this Brobdingnagian fashion! Let the reader consider this hydraulic analog carefully. It produces nearly all of the essentials of the electrical case. The conducting vapor in the arc of a circuit breaker is somewhat analogous to mud as a dam-building material.

Very little need be said of characteristic line surges in connection with opening of switches, except in the case of very long lines. When a line is short, or only moderately long, what takes place may be described quite accurately in terms of the simple ideas of elementary alternating-current theory, where current values are supposed to rise and fall simultaneously throughout an entire

circuit. The formation of a long arc between line wires in air, and the quick snapping out of such an arc, is the only case known to the writer where an electric wave disturbance can be produced by opening the circuit of a transmission line of moderate length, and the essential features of this case are shown in Fig. 17. Imagine the system to be short-circuited by an arc at the distant end D of the transmission line, voltage being reduced to a negligibly small value over the whole line, and a large current I established in the line. The generator is to be thought of as having a large inductance so that the generator current cannot change perceptibly during the very short time required for the characteristic line surges. When the distant end of the line is opened, a ribbon wave shoots towards the generator, is completely reflected at the generator with reversal of current, again completely reflected at the opened end D of the line with reversal of current, and so on. The first lap of this ribbon wave wipes out the current in the line and lays down a certain voltage E ($= aI$). The second lap of the ribbon wave lays down a double voltage, and the original current. The third lap wipes out the current again, and lays down a voltage equal to $3\,E$, and so on.

It must not be imagined that the sending out of a ribbon wave depends upon a continued supply of energy at the point where the ribbon wave originates. Thus in Fig. 17 the ribbon wave is superposed upon the initial current I, and the first lap of the ribbon wave wipes out this current. Therefore, since the current is zero, there is no energy flow at all from the opened end. The second lap of the ribbon wave lays down the original current I and a doubled voltage $2E$ ($= 2\,aI$), and this combination of voltages and current represents the flow of energy from the generator into the line.

DISCUSSION ON "SOME SIMPLE EXAMPLES OF TRANSMISSION LINE SURGES" (FRANKLIN), WASHINGTON, D. C., APRIL 24, 1914.

J. Murray Weed: The steepest wave fronts which are produced in the practical operation of electrical systems are those caused by the sudden making or breaking of a circuit. A discharge to ground would come under this classification, although this may not constitute the making of a circuit which it is desired to make. It does not seem likely, however, that the making of a circuit which takes place by the rupturing of air, oil, or some other dielectric, would result in the rectangular waves which are presented in Dr. Franklin's paper. When we consider the velocity of 186,000 miles a second, it becomes obvious that a phenomenon which is instantaneous, so far as our ability to measure time is concerned, may distribute its effects over a very considerable length of a transmission line. Furthermore, it is my belief that if, by any means, a perfectly abrupt or sheer wave front were produced in a transmission line, it would be very rapidly decomposed, and that at a considerable distance from the point of its formation it would have become considerably tapered.

We do have good evidence, however, that wave fronts may be produced which are so steep as to be dangerous to the turn-to-turn insulation of inductive apparatus; sometimes so steep, in fact, as to rupture insulation which has been specifically designed to withstand this sort of disturbance. Moreover, there is no doubt that most of the voltage disturbances in transmission lines originate as traveling waves, or impulses. The method of treatment used by Dr. Franklin is very useful in investigating the behavior of such disturbances and also in investigating various methods of protecting from these disturbances. They have been used already to good advantage by several German writers, notably K. W. Wagner. I myself have been making a study of this nature, some of the more important results of which I hope to publish in the near future.

The written discussion which I have submitted gives a treatment somewhat parallel to Dr. Franklin's, in which I have undertaken to make the subject of how and why waves travel, clear to one who has not given the subject any study, but who has, to begin with, merely a fundamental knowledge of inductance, capacity and resistance. It may be, also, that a concise statement of this matter will be of interest to those who are more familiar with the subject.

J. Murray Weed (by letter): If we consider a generator, of zero impedance and of voltage E, connected instantaneously to a pure inductance, the result is a gradual growth of current, such that

$$L\frac{di}{dt} = E \tag{1}$$

The current which enters the inductance at one end is leaving it at the other end at the same instant, since there is no capacity within the inductance for storing up current. The value of L involved in equation (1), therefore, is the total inductance, and since there is no resistance, the growth of current is uniform and continuous.

If the same generator be suddenly connected to the end of one wire of an indefinitely long transmission line of zero losses by closing the switch, our conception of the method in which the line would be charged is as follows:

The capacity of the first element of the line is instantly charged. But current must flow through the inductance of this element to charge the second element, and this requires an instant of time. After the second element is charged there is no further growth of current in the first element, since there is no difference of potential applied to this element. The current set up at the first instant merely continues to flow, supplying the necessary charging current for successive elements of the line, and current grows in but one element at a time, this growth being by an instantaneous change from $i = 0$ to $i = I$. The current I and the electrostatic charging of the line to voltage E advance together with a sheer wave front, so that the total voltage of the circuit appears at the front of the wave. We find the relation between this action and the growth of current in the pure inductance of the first case, as follows:

Equation (1) may be written in the form

$$d\frac{(Li)}{dt} = E \tag{2}$$

and for the transmission line, since we assume an instantaneous growth of current from zero to a constant maximum value in successive elements of inductance, we may say that we have constant current, with gradual increase of inductance, so that equation (2) becomes

$$I\frac{dL}{dt} = E \tag{3}$$

If L_0 = the inductance per unit length of the line, this becomes

$$I L_0 \frac{dy}{dt} = E$$

or

$$I L_0 dy = E dt \tag{4}$$

where y = distance along the line.

If Y = the total length of the line, and T = the time required for the charging wave to traverse the line, the integration of equation (4) gives

$$I Y L_0 = E T \tag{5}$$

Considering now the relation between current, voltage, and the capacity of the line, we find similarly the equation

$$E\,C_0\,dy = I\,dt \tag{6}$$

where C_0 is the capacity per unit length of the line. The integration of this equation gives

$$E\,Y\,C_0 = I\,T \tag{7}$$

From equations (5) and (7) we obtain directly the time required for the charging wave to traverse the line,

$$T = Y\,\sqrt{L_0\,C_0} \tag{8}$$

and since the velocity equals the length of the line divided by the time, we have

$$v = \frac{1}{\sqrt{L_0\,C_0}} \tag{9}$$

From (5) and (7) we also obtain

$$\frac{L_0\,I^2}{2} = \frac{C_0\,E^2}{2} \tag{10}$$

Since the first member of this equation represents the electromagnetic energy per unit length, and the second member the electrostatic energy per unit length, equation (11) shows the equality between the electrostatic energy and the electromagnetic energy of the advancing wave, which is a characteristic of all pure traveling waves. The total energy per unit length of the charging wave thus is

$$W = \frac{L_0\,I^2}{2} + \frac{C_0 E^2}{2} = L_0\,I^2 = C_0\,E^2 \tag{11}$$

This energy per unit length multiplied by the velocity of the wave gives the power absorbed from the generator. Thus, from equations (9) and (11),

$$P = L_0\,I^2\,\frac{1}{\sqrt{L_0\,C_0}} = I^2\sqrt{\frac{L_0}{C_0}} \tag{12}$$

and

$$P = C_0\,E^2\,\frac{1}{\sqrt{L_0\,C_0}} = \frac{E^2}{\sqrt{\frac{L_0}{C_0}}} \tag{13}$$

So far as the generator is concerned, with an indefinitely long transmission line, this power is lost, just as much as though it had been consumed by the resistance

$$R_0 = \sqrt{\frac{L_0}{C_0}} \tag{14}$$

The quantity $\sqrt{\frac{L_0}{C_0}}$ is, in fact, measured in ohms, and may be called the wave resistance of the line.

From the equation (**11**) or directly from equations (**5**) and (**7**), we have also

$$I = \frac{E}{\sqrt{\frac{L_0}{C_0}}} = \frac{E}{R_0} \tag{15}$$

Thus Ohm's law may be applied to a transmission line with respect to traveling waves, and shows how much current will flow into the line with a given voltage applied. This must be restricted, of course, to the initial period of charging the line.

If we examine a point in the line after the wave front has passed, we find the constant current I flowing at the constant voltage E, which is the generator voltage, supplying the power

$$P = E\,I = I^2 R_0 = \frac{E^2}{R_0} \tag{16}$$

These values of P are the same as that given by equation (**13**).

Now, if the generator voltage is suddenly reduced to zero, current ceases to enter the line from the generator. One might, at first thought, expect the current to begin to flow back from the line into the generator. This, however, is not the case. The wave of current and voltage continues to progress in the line. The rear end of the wave is similar to the front end, except that the voltage E existing in the line, here acts in a direction toward the generator, instead of away from the generator, and we have here a counter e. m. f. which is away from the generator, due to the cessation of current in that inductance from which the rear end of the wave is passing, whereas the counter e. m. f. at the front of the wave is toward the generator, due to the current entering the inductance which is in advance of the wave. Kirchoff's law for voltage is satisfied at both ends of the wave, as expressed for the front end by equation (**4**). The same equation may be used for the rear end, but the opposing e. m. f's are reversed with respect to the positive direction in the circuit. If we change signs on both sides of the equation to account for this, we have

$$-I\,L_0\,dy = -E\,dt \tag{17}$$

This equation for the rear end of the wave may be looked upon as belonging to a wave front of opposite polarity, the front of a wave of negative current and negative voltage, superposed upon the former wave of positive current and positive voltage, and thus reducing both current and voltage to zero.

The above deductions were made with respect to an abrupt or sheer wave front. If a practical generator, or generator and step-up transformer, of large inductance, be suddenly connected to the end of a line, the charging wave will not be abrupt, since the current I must grow in the inductance of the generator. The growth of current and voltage at the entrance of the transmission line are logarithmic, as expressed by the equations

$$i = \frac{E}{R_0}\left(1 - \epsilon^{-\frac{R_0}{L}t}\right) \tag{18}$$

and

$$e = E\left(1 - e^{-\frac{R_0}{L}t}\right) \tag{19}$$

where $R_0 = \sqrt{\frac{L_0}{C_0}}$ is the wave resistance of the line, as found above for the abrupt wave, L is the inductance of the generator and t is the time measured from the instant of closing the switch. Substituting the value

$$t = y\sqrt{L_0 C_0} \tag{20}$$

these equations become

$$i = \frac{E}{R_0}\left(1 - e^{-\frac{L_0}{L}y}\right) \tag{21}$$

and

$$e = E\left(1 - e^{-\frac{L_0}{L}y}\right) \tag{22}$$

which give the current and voltage at a point in the wave distant y from the tip of the wave which entered the line at the first instant.

That such a tapered wave, or in fact a wave of any shape, will follow the same laws as the wave with abrupt front and rear, is easily inferred by thinking of the tapered wave as made up of infinitesimal abrupt waves, distributed in time, or in space. Equations (**4**) and (**6**) can be applied to each of these differential waves and integrated with respect to distance and time, giving in lieu of equations (**5**) and (**7**),

$$di\, Y L_0 = de\, T \tag{23}$$

and

$$de\, Y C_0 = di\, T \tag{24}$$

All of these differential waves, therefore, follow the same laws of propagation, reflection and refraction as a finite abrupt wave.

Thus, the velocity of each element of the wave will be the same, and the same proportions are reflected, and refracted. The wave shape of the tapered or irregular wave, obtained by the superposition of all of the differential elements, is therefore preserved, and the same proportionality will exist between the original wave and its reflections and refractions as with the abrupt wave; although this statement would have to be modified where the reflecting agent is reactive.

Some consideration of the nature of so-called reflections of the traveling wave will make this subject clearer to those who are not already familiar with it. Thus, for instance, at the instant when the abrupt wave reaches the end of the line, we find the entire line charged to voltage E, and the current I flowing throughout its length. The condition at this instant is the same, whether the line be open or closed. If the line is open, since the current can not flow out at the end of the line, it supplies additional charge to the end of the line, and so builds up the voltage to a higher value than E. The question as to how high this voltage will build has been answered by saying that the wave is completely reflected, with negative current and positive voltage, this reflected wave superposed upon the oncoming wave giving zero current and double voltage.

This statement, however, does not give the true fact, but a fictitious condition which is equivalent to the fact. The fact is that the line retains its charge corresponding to the voltage E, while the current I acts in the same manner as it would if it had been flowing through the line, with no voltage at all present, and were suddenly interrupted at the end of the line. With the building up of a certain voltage E' in the last element of the line, current must cease in the next to the last element. Otherwise the voltage would continue to build up indefinitely. Voltage will then build up in the next to the last element, with cessation of current in the preceding element, etc. The voltage E^1 is acting in a direction against the current or the negative direction, while an equal counter e. m. f. in the positive direction is produced by the reduction in the amount of inductance occupied by the current I. This balance of e. m. f's is expressed by equation (**4**) with the appropriate changes in signs. Thus

$$I L_0 (- dy) = -E' dt \tag{25}$$

This equation may be looked upon as applying to a wave of negative voltage and positive current, traveling in the negative direction, and leaving the line charged to the voltage E'. In the case which we are considering, the line was already charged to voltage E, so that the resultant voltage is now $E + E'$.

If we change signs on both sides of equation (**25**), thus transferring it to the other side of the wave front, we have

$$- I' L_0 (- dy) = E' dt \tag{26}$$

This equation applies to the front of the fictitious reflected wave of positive voltage and negative current, which is supposed to be superposed upon the original wave.

The same considerations which gave us the current which will enter a line with voltage E applied (**15**), will now give us the voltage which will be built up in the line by the current I, namely,

$$E' = I R_0 \tag{27}$$

If reference is made to the fictitious reflected current, which is no doubt the more convenient, we must take account of the negative sign, and (**27**) becomes

$$E' = -I' R_0 \tag{28}$$

where I' is negative.

In the case of the closed-ended line, instead of the line retaining its charge corresponding to voltage E, and the current I building up an additional voltage E', which is equal to E, we find that the current I is uninterrupted, while the voltage E is permitted to set up an additional current I', which is equal to I. Equation (**28**) applies here also, but in this case I' is positive and E' negative.

Professor Franklin has spoken of the effects of line losses as usually small. It can be shown that, as ordinarily considered, they have no effect in destroying the abruptness of the wave, but that they reduce the height of the wave front in accordance with the equation

$$E_y = E_1 e^{-\left(\frac{g}{2G_0} + \frac{r}{2R_0}\right)y} \tag{29}$$

where E_y is the voltage at the wave front, E_1 is the voltage with which the wave enters the line, y is the distance that the wave has traveled, g and r are the insulation conductance and the resistance per unit length of line, and G_0 is the reciprocal of R_0, and may be called the wave conductance of the line.

There is, however, another element of loss, and of energy absorption, which exists only in the wave front, and which does destroy its abruptness. The rapidity of this action I have not yet determined. The action referred to is that of skin effect, the current at the extreme front of an abrupt wave being all at the surface, and becoming gradually diffused after the wave front has passed. I have found that the energy subtracted from the wave within the region wherein this diffusion takes place, corresponds to a resistance of 30 ohms.

With a perfectly abrupt wave front this resistance will be effective with respect to the total current at once, and so will decompose the wave front rapidly. As soon as the wave front becomes tapered, the extra wave front resistance will be effective with respect to only a part of the current at a time, and the energy absorbed is thus reduced, as well as distributed over a greater distance, or longer portion of the wave. This process

of reducing the energy absorbed, and distributing it over greater distance, goes on progressively.

A. G. Webster: To allay the doubts of the last speaker, Mr. Weed, who said that it was impossible for the corners to persist, I will say that that is absolutely true in real lines, but Dr. Franklin has the gift of making things very simple by making certain assumptions.

Some of us are familiar with sound. It happens that sound waves are easier to experiment on than electric waves. The theory given by Dr. Franklin, and the theories advanced in the papers by Mr. K. W. Wagner, in which you will find a number of oscillograms, show these things, how you may have corners in a real circuit, though the corners round off, and the theory is exactly the same as the transmission of plain sound waves. You know that organ pipes correspond exactly to the circuit with a certain amount of inductance, and with a certain amount of capacity, which is elasticity of air. Any wave that enters at one end proceeds to the other end, and is reflected back if the end is open. If the pressure is that of the open air there cannot be any difference, and the pressure wave is reflected back. So, if the end is open there can be no current, and the current is reflected back. On the other hand, if the end is closed, there can be no displacement, because air cannot move against a wall, it being a longitudinal wave. If the electrical wave has an open end where there is no current the potential is doubled. Say that a wave runs back and forth in this tube, it is different at the two ends and has to go back and forth four times before it gets to its former condition, and, therefore the wave length will be four times the length of the tube.

Twenty-one years ago I made some experiments on these surges, not on a cable, for I had none, but on a wire some five or six hundred feet long. On the basis of my experiments I announced that I would present a paper at the International Electrical Congress in Chicago, in 1893, spoken of by President Mailloux earlier this evening. I made a few experiments, enough to justify me in sending in the title of the paper, but as it developed, they were not enough to justify the preparation and reading of a paper, so I withdrew it. The apparatus with which to conduct the experiments was made, but on account of mechanical difficulties it was put aside. Since Dr. Whitehead asked me last week if I would speak on this paper, I have put up a wire again, and made further experiments. I may say that all of Mr. Wagner's experiments were made on an artificial line, a very remarkable line made of coils and condensers and representing all sorts of cables and all sorts of lengths, and his conditions, though simpler, are more like reality than Dr. Franklin's, for he allows you to put in a damping term. My own experiments have borne out the same idea. Such a wave, instead of being a ribbon wave, falls off, as was stated by the last speaker. There is a corner on it, but

this corner goes along with the velocity of light, and when it has reached a given point, it has fallen off by a definite fraction. I showed the proof of that in my book some seventeen years ago. The theory was given some twenty-five to thirty years ago by Oliver Heaviside.

This line that I speak of was merely a copper wire strung up, and a charge is put on. The other end of the wire, which has been brought back by a sufficiently remote route, is connected with an electrometer, and about two-millionths of a second after this discharge has been put on the electrometer is disconnected. The thing is done again, moving the micrometer up so as to make it, say, a millionth of a second, but as this line was only three hundred meters long, it took a millionth of a second to traverse it, and you see the instrument is put under very serious demands, and I am free to say it is not sensitive enough to give satisfactory performance on a very short line. I would like to have a line two or three miles long. A battery is put on here—we will say it is positive. You can easily see that the electrometer can give absolutely no negative readings unless there are surges. As a matter of fact we get a certain number of positive readings scattered around, but we get some negative readings, at least half as big as the positive readings. My instrument is not perfect, but it is sensitive, it will measure to one two-millionth of a second, but it will not do the same thing for one ten-millionth of a second. If I had a longer line I could show these things in a better experiment. That is the experiment I tried to do twenty-one years ago—I did not forget it, but put it aside, and last week I got what I may call positive results.

As has been said, in a real line the wave goes to 186,000 miles per second, but few lines are as long as that. These things happen quickly; that they are real no one doubts; that the potential may be doubled and climb up by steps, etc., all those things are a consequence of theory.

In these papers of Dr. Wagner's you will see real oscillograms; the whole thing is very clear. There is a charge put on a resistance, the potential rises immediately, falls a little, goes up again, and comes back, and so on, and this approaches an asymptote, and then the potential goes down, by successive steps. This was not on a real line, it was on an imitation line, but I presume everybody here believes a statement of Prof. Pupin, which he has evolved from his experiments, that such lines do imitate the real lines to great perfection, provided the coils are subdivided finely enough.

A. Hamilton-Ellis (by letter): I do not agree with the author that very little need be said in connection with the opening of switches on short lines.

In a case which occurred some time ago, at the station where the writer is, the switching-off of a bank of three single-phase transformers, connected in delta on the primary, for supply-

ing a 750-kw. synchronous converter, resulted in wrecking the switch and almost wrecking the cell structure. The transformers were only energized at the time, the converter being shut down.

The supply was at 6600 volts, 25 periods, with one phase earthed, the neutral of the generator being insulated. Between the switch and transformers were approximately 90 ft. of three-core, paper-insulated, lead-covered cable of 0.075 sq. in. section. An examination of the switch, or what was left of it, showed the appearance of an arc having been broken, but it was extremely doubtful.

However, doubts were soon put at rest, for, shortly afterwards, one of the transformers, which had the appearance of an arc having taken place inside it, was disconnected and a generator was run directly upon it. The connection between the generator switch and the transformer was made with 7/16 stranded cable, one pole being grounded. On reaching 6600 volts, the generator switch was accidentally opened, with the result that the switch was wrecked, this wrecking taking place across the terminals outside the switch. An examination of the switch contacts failed to show any sign of an arc having taken place, and the transformer was later found to be all right.

Further tests were carried out with an oscillograph, when it was found that the voltage rise was approximately 5½ times normal, when the switch was opened with these transformers on magnetizing current alone.

Perhaps the author will be able to give a reason for the occurrence. Allowing that in the first instance an arc was drawn out and that the condenser effect of the cable was sufficient to quench it suddenly, the cause is not so self-evident in the second case.

However, the point I wish to bring forward is, that even in the case of the shortest of connecting lines between the generator busbars and the apparatus that is connected thereto, there is every possibility of these surges taking place.

Presented at the 294th Meeting of the American Institute of Electrical Engineers, Washington, D.C., April 25, 1914, under the auspices of the Electrophysics Committee.

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A MILLIAMPERE CURRENT TRANSFORMER

BY EDWARD BENNETT

ABSTRACT OF PAPER

(1) It is pointed out that by the use of a current transformer having a primary to secondary current ratio of the order of 1 to 100, oscillograms can be obtained of the charging current of a single high-tension insulator or of a few feet of high-tension transmission line; that is, oscillograms of currents of the order of 0.1 to 0.5 milliampere may be obtained.

(2) The drawings and specification are given for a transformer for this purpose.

(3) The transformer relations are discussed; the methods of determining the transformer constants are outlined, and the performance of transformers constructed in accordance with the specifications is determined.

(4) A series of oscillograms is given to illustrate some of the applications of the transformer, such as to the study of corona, high-tension insulators, and leakage currents in evacuated lamps.

I—INTRODUCTION. PURPOSE OF THE TRANSFORMER

IN AN investigation of the merits of wooden insulator pins and of the causes of pin charring, conducted in 1908 for the Telluride Power Company, the writer had occasion to construct a current transformer which would permit of obtaining oscillograms of the displacement current across a single high-tension insulator. Since then a similar transformer has been used to determine the effect of corona on the wave form of the displacement current between a 10-ft. (3-m.) length of wire and a concentric 14-in. (35.56-cm.) pipe.

The first transformers were designed to have a current ratio of 100, but on test developed a ratio of only 89; moreover, it was evident that high harmonics were getting through the primary winding as a displacement current from layer to layer.

Computations, based on the assumption that the primary was wound in layers, had indicated that the displacement current between layers at 60 cycles would be less than 0.2 per cent of the total current. After the test, these computations were rechecked with the same results as before, and for some time the discrepancy remained inexplicable. The cause of the discrepancy was eventually discovered and eliminated only by a chance observation.

In view of this experience and of the merits of the transformer for certain lines of investigation, a description of the construction and characteristics of the perfected transformer would seem to be warranted and is herewith presented.

Purpose of the Transformer. A deflection of one centimeter on oscillograms from the oscillograph used is obtained with a

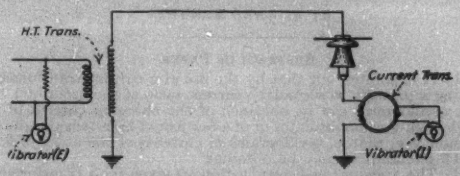


FIG. 1—CONNECTIONS FOR INSULATOR OSCILLOGRAMS

current of from 0.05 to 0.08 peak ampere. Oscillograms with a peak deflection of less than 0.5 cm. are not very satisfactory, therefore the smallest current which will give a satisfactory oscillogram when passed directly through the vibrator of the oscillograph is 0.02 r.m.s. ampere.

The displacement current at the working voltage from the line

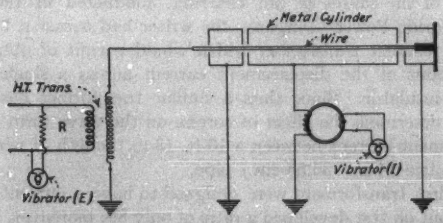
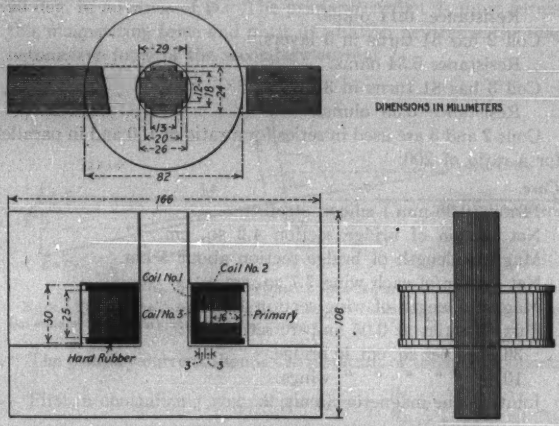


FIG. 2—CONNECTIONS FOR OSCILLOGRAM OF THE CHARGING CURRENT OF A WIRE

wire to the pin of a single high-tension insulator is about 0.0002 ampere at 60 cycles, that is, it is approximately the same as the charging current of six ft. (1.8 m.) of No. 00 B. & S. conductor at 34.6 kv. to ground. Oscillograms of these currents may be obtained by using a current transformer with a current ratio of 100 as shown in Figs. 1 and 2.

II—Description of the Transformer

The construction and dimensions of the transformer are shown in Figs. 3 and 4. Primary and secondary coils are wound on a single hard rubber spool, the secondary coils being at the bottom of the spool. The magnetic circuit comprises a short bridge section within the spool and two wings of greater length but each having 1.8 times the cross-section of the bridge. The laminated core is clamped between two maple blocks on which are mounted the binding posts in which the coils terminate.



Figs. 3 and 4—Milliampere Current Transformer

Specification

Rating.

Secondary current range 0.01 to 0.1 ampere.

Ratios of current transformation 100 and 200.

Primary current range 0.00005 to 0.001 ampere.

Frequency 60 cycles.

Resistance of external circuit 0.6 ohms.

Reactance " " " negligible.

The 200 ratio is for use only in those cases in which very exact phase relations are not essential.

Primary Winding.

16,200 turns of 38 B. & S. gage enameled copper wire.

Mean diameter of turn 6.3 cm.
Total length of wire 3210 meters.
Measured resistance 6650 ohms.

The wire is not wound in single layers but in "sections" of about 600 turns each with a layer of 0.04-mm. tissue paper between sections.

Secondary Winding.

Number of coils 3.
Size of wire No. 20 B. & S. double silk covered copper.
Coil 1 has 1 layer of 27 turns.
Resistance, 0.11 ohms.
Coil 2 has 81 turns in 3 layers.
Resistance 0.34 ohms.
Coil 3 has 81 turns in 3 layers.
Resistance 0.38 ohms.

Coils 2 and 3 are used in series for a ratio of 100 and in parallel for a ratio of 200.

Core.

14-mil (0.36-mm.) silicon steel.
Net section of bridge section 4.2 sq. cm.
Magnetic length of bridge section about 5 cm.
Net section of each wing 7.7 sq. cm.
Magnetic length of wing section 15 cm.
Flux densities at 0.05 ampere secondary:
36 lines per sq. cm. in bridge.
10 " " " " " wings.
Joints in the magnetic circuit, 2.

III—Transformer Relations

Fig. 5 is a vector diagram showing the phase relations of currents, voltages, and magnetic flux when the transformer is connected for a ratio of 100 and is delivering 0.05 ampere (effective value) to the secondary circuit. Unless otherwise stated, the following discussion all relates to the 100 to 1 connection of the transformer.

In this diagram,

if $I_2 = 0.05$ ampere represents the current in the secondary then

$E_2 = 0.05\ (r_2 + jx_2)$ represents the voltage that must be induced in the secondary by the magnetic flux.

$E_2 = I_2\ (r_2 + jx_2)$ is the resultant of the two components,

I_2r_2, in phase with the secondary current, and

jI_2x_2, leading the secondary current by 90 deg., where

r_2 is the resistance of the secondary winding plus the resistance of the external circuit supplied by the secondary, and

x_2 is the reactance of the secondary winding due to leakage flux embracing the secondary alone, plus the reactance of the external circuit.

The secondary voltage E_2 is induced by the mutual magnetic flux φ, 90 deg. in advance of and directly proportional to E_2.

To drive the flux φ through the magnetic circuit there is required a magnetizing force consisting of two components, a wattless component M in phase with φ, and a power component W, 90 deg. in advance of φ. The primary current I_1 must furnish this magnetizing force and must in addition neutralize the magnetomotive force of the secondary current I_2.

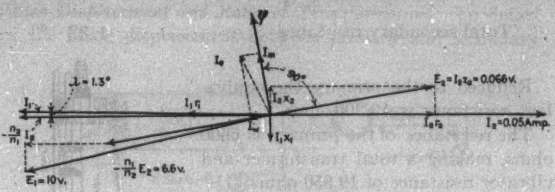


FIG. 5—TRANSFORMER DIAGRAM

NOTE. The exciting current I_e and its components I_m and I_w are drawn to 10 times the scale of the primary and secondary currents.

The primary current then is the resultant of three components:

First, a neutralizing component $I_n = -\frac{n_2}{n_1} I_2$ or in phase opposition to I_2.

Second, a wattless exciting component I_m in phase with φ.

Third, a power exciting component I_w, 90 deg. in advance of φ.

The voltage E_1 consumed in the primary of the transformer is made up of three components:

First, the voltage consumed by the mutual flux φ,

$$= -\frac{n_1}{n_2} E_2.$$

Second, the voltage consumed by resistance in the primary, a voltage in phase with I_1, and equal to $I_1 r_1$.

Third, the voltage consumed by leakage flux linking with the primary alone, a voltage 90 deg. in advance of I_1 and equal to $jI_1 x_1$.

It is seen from this diagram that the reversed secondary current leads the primary current by a small angle, λ, whose tangent is approximately equal to the component of the exciting current in quadrature to the load current divided by the load current. Furthermore, the ratio of the secondary to primary current is less than the ratio of primary to secondary turns, due to the component of the exciting current in phase with the load current.

IV—Determination of the Transformer Constants

Resistance. The resistance of the secondary circuit is as follows:

Secondary winding	0.62 ohms
Leads to the oscillograph (negligible)	
Vibrator of the oscillograph	0.6 "
Total secondary resistance	1.32 "

Reduced to the primary the equivalent resistance is 13,200 ohms.

The resistance of the primary is 6600 ohms, making a total transformer and vibrator resistance of 19,850 ohms.

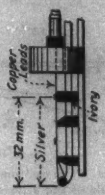


Fig. 6—Modified Vibrator

It will be noted that the resistance given for the vibrators, (0.6 ohms), is only one-half of the resistance of the standard vibrators. This reduction in the resistance has been effected by modifying the vibrators as shown in Fig. 6. This modification eliminates useless silver strip, reducing the length of the strip to one-half the standard length, without in any way affecting the period or sensitiveness of the vibrator. It is of course out of the question to fuse vibrators used in the secondary of the current transformer, because of the high resistance of the fuse.

Reactance. The reactance of the external part of the secondary circuit is negligible in comparison with the reactance of the secondary winding.

The separate reactances of primary and secondary due to leakage flux cannot be computed from the transformer dimensions with any degree of accuracy. The combined leakage reactance of primary and secondary can, however, be obtained experimentally by taking an oscillogram with the connections shown in Fig. 7. Fig. 8 (film 203) is a characteristic oscillogram taken with these connections. The current I in the secondary lags about 12 degrees

behind the potential E across the primary. With a transformer and a vibrator resistance of 19,850 ohms, a lag of 12 deg. indicates a leakage reactance of 4800 ohms at 60 cycles.

It will be approximately correct, and will introduce no appreciable error to apportion half of this to the primary and half to the secondary, thus making the primary reactance 2400 ohms and the secondary reactance 0.24 ohms. Fig. 5 has been constructed on this basis.

Flux Densities. With a total secondary impedance of 1.33 ohms $= (1.32 + j\,0.24)$, the secondary voltage at 0.05 ampere is 0.066 volt. To generate this voltage, the flux densities must be 36 lines per sq. cm. in the bridge and 10 lines per sq. cm. in the wings. Data are not available for the predetermination of the exciting current at these low flux densities.

Phase Displacement and Ratio of Transformation. To determine the phase displacement between primary and secondary

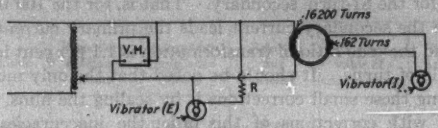


FIG. 7—CONNECTIONS FOR THE DETERMINATION OF TRANSFORMER REACTANCE

currents and the ratio of transformation, oscillograms were taken with the connections shown in Figs. 9 and 12. As shown in Fig. 9, a 60-cycle current, measured by a voltmeter A, is passed through one of the 81-turn coils and through the vibrator P. The second 81-turn coil is connected through an adjustable resistance R to the vibrator S, which was calibrated before and after these tests.

For small variations in the resistance of the secondary circuit, the angle of phase displacement and the percentage reduction in the multiplier are approximately proportional to the secondary resistance. The additional resistance R, which was varied from zero to three ohms, was inserted for the purpose of increasing the angle of phase displacement, thus permitting of its more accurate determination from the films. Figs. 10 (film 200) and 11 (film 201) are characteristic films obtained in this manner. By scaling the films, it is found that the transformer with an 81-turn secondary has a ratio of transformation 3.2 per cent less

than the ratio of the turns, and the secondary current leads the primary by an angle of 3.6 deg. These are the constants of the transformer when connected for a ratio of 200 to 1 with a total secondary resistance of 0.94 ohms.

When, however, the transformer is connected for a ratio of 100 to 1, with a 162-turn secondary of 1.32 ohms resistance, the angle of phase displacement and the percentage reduction in the ratio will be approximately $\left(\frac{1}{4} \times \frac{1.32}{0.94}\right)$ or 0.35 of the corresponding

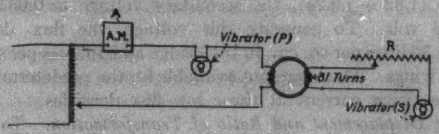


FIG. 9 —CALIBRATION OF CURRENT TRANSFORMER

values for the 81-turn secondary. That is, for the 100 to 1 connection the secondary current leads the primary current by 1.3 deg. and the true ratio of transformation is 1.1 per cent less than the ratio of turns. It should be noted that the only method of obtaining these small corrections is by scaling the films. When dealing with corrections of this order the inaccuracies of the method are such that the above *corrections* may be in error by 25 per cent.

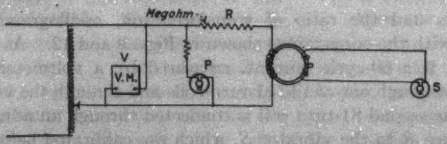


FIG. 12—CALIBRATION OF CURRENT TRANSFORMER

A second method of calibrating the transformer is shown in Fig. 12. In this method a known non-inductive resistance R of about one megohm is connected in series with the 16,200-turn primary, and a known voltage, measured by the voltmeter V, is impressed across the primary and the megohm resistance. The primary current lags 0.2 deg. behind, or is practically in phase with, the impressed voltage, which is recorded by the vibrator P. The secondary current is recorded by the calibrated vibrator S. The primary current is computed from the

impressed voltage and the known resistance, while the current in the secondary is obtained by scaling the oscillograms. A number of calibrations made in this manner confirm the results obtained with the Fig. 9 connections.

Constants of the Transformer for Higher Harmonics. The constants of the transformer have been experimentally determined only at 60 cycles. From these tests conclusions may be drawn as to the performance for a limited range of higher frequencies.

In the following table are listed the computed values of the secondary reactance and of the secondary impedance to the fundamental frequency, (60 cycles), and some of the higher harmonics. The fourth column of the table shows the relative flux densities required to drive the same secondary current through these impedances at the corresponding frequencies; the fifth column shows the relative values of the eddy currents, and the sixth the relative values of the hysteresis losses.

Harmonic	Secondary reactance Ohms	Secondary impedance Ohms	Relative flux density	Relative value of eddy currents	Relative hysteresis loss
1st (60 cycles)	0.21	1.33	1.00	1.0	1.0
3rd	0.63	1.46	0.37	1.1	0.7
5th	1.02	1.67	0.25	1.3	0.5
7th	1.47	1.97	0.21	1.5	0.6
9th	1.89	2.30	0.19	1.7	0.6
15th	3.16	3.43	0.17	2.5	0.9

An inspection of this table in connection with the vector diagram, Fig. 5, indicates that:

a. The angle of lead of the secondary current and the discrepancy between transformer ratio and ratio of turns, may be expected to become smaller and smaller for the third, fifth and seventh harmonic.

b. The angle of lead of the secondary current will pass through zero and become an angle of lag, between the fifth and ninth harmonic.

c. The constants of the transformers for all harmonics up to the fifteenth will be extremely satisfactory.

Displacement Currents. There remain to be considered the possible transformer errors resulting from the passage of primary current through the transformer as a displacement current from turn to turn or layer to layer. For the purpose of deter-

mining the order of magnitude of this current, assume the primary is wound evenly in layers, each layer starting from the same side of the spool. With a wall thickness of 0.008 mm. of enamel insulation surrounding each wire, the estimated capacity between adjacent layers is less than 8×10^{-9} farads, or the capacity reactance to 60 cycles is 340,000 ohms. With 0.0005 ampere in the primary the voltage between layers is 0.13 volt and the displacement current between layers will be 4×10^{-7} ampere or 0.08 per cent of load current.

The first two transformers constructed were wound with 40,000-turn (5 miles of wire) primary coils of 0.08-mm. enameled wire. For these transformers the displacement current between layers, computed under the assumption of uniform layers, was 0.2 per cent of the load current. This seemed low enough, and accordingly the transformers were wound with no additional insulation between layers. As noted in the introduction, these transformers were designed for a ratio of approximately 100, but on test developed a ratio of only 89; moreover, higher harmonics were not faithfully reproduced in the secondary. For some time the cause of this discrepancy between computed performance and performance on test could not be discovered. Finally, in unwinding one of the transformers the observation was made that the nth turn was not always adjacent to the ($n-200$th) and ($n+200$th) in the preceding and following layers,—as would be the case with uniform layers, and as assumed in the computations,—but occasionally came in contact with turns farther removed from it, as the ($n \pm 900$th) or the ($n \pm 1400$th). The explanation of this is as follows:

In winding a fine wire the turns have a decided tendency to override and "pile up" several turns deep at some parts of the layer, and to run ahead of the correct position at other parts. Where the wire runs ahead of its correct position, a portion of the lower layer is left uncovered, with the result that turns in the neighborhood of the ($n \pm 900$th) or ($n \pm 1400$th) turn may come in contact with these uncovered portions of the lower layers. The difficulty of winding in absolutely uniform layers is so great that the wire was allowed to pile up and run ahead in this manner. After observing this condition of the winding it became evident that the loss in primary ampere-turns might be far higher than the 0.2 per cent computed for uniform layers; this loss in ampere-turns would be due to the "bridging" of sections of the winding at considerable difference

FIG. 8 [BENNETT]

FIG. 10 [BENNETT]

FIG. 11 [BENNETT]

FIG. 14 [BENNETT]

FIG. 17 [BENNETT]

FIG. 18 [BENNETT]

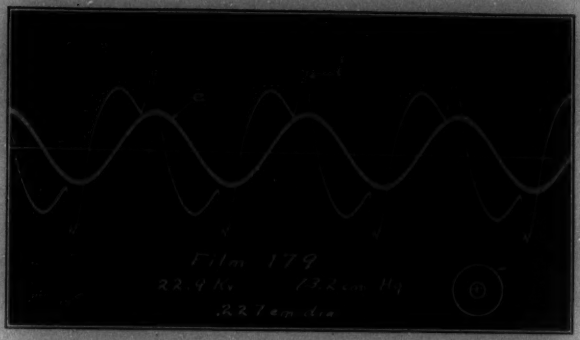


FIG. 19 [BENNETT]

FIG. 20 [BENNETT]

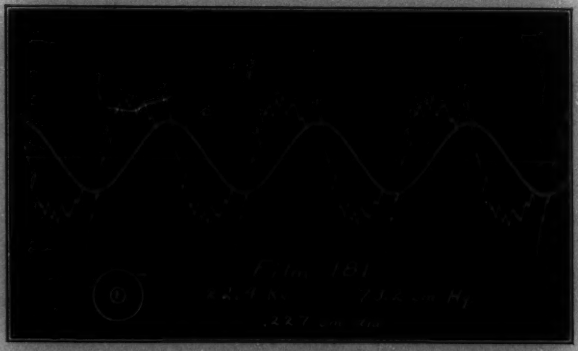


FIG. 21 [BENNETT]

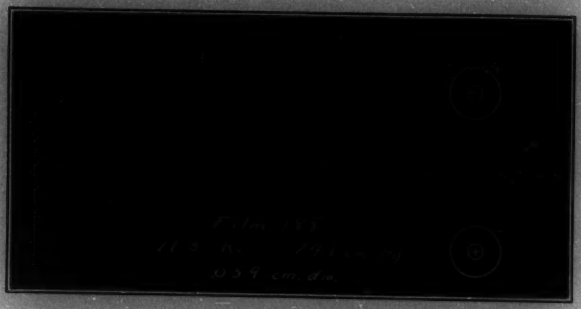


FIG. 22 [BENNETT]

FIG. 23 [BENNETT]

FIG. 24 [BENNETT]

FIG. 25 [BENNETT]

FIG. 26 [BENNETT]

FIG. 27 [BENNETT]

FIG. 28 [BENNETT

FIG. 29 [BENNETT]

FIG. 30 [BENNETT]

of potential by the capacity between the turns in contact. The displacement current between these sections in contact would be shunted from the portion of the winding between the turns.

The use of paper insulation between layers is a remedy which immediately presents itself. A layer of paper between each two layers of wire would result in a primary coil with a much larger mean diameter. This in turn means a very appreciable and objectionable increase in the leakage reactance.

The primary of the transformer described in this paper was accordingly wound in sections of about 600 turns each, with paper insulation between the sections only. Each section was the full width of the coil and on the average three turns deep. The winding of a section started at one face of the spool, advanced toward the other face, the turns piling up two to four deep all along, and terminated when the other face of the spool was reached. A single thickness of 0.04-mm. tissue paper was wrapped around the completed section, and the next section was wound on this paper, and so on. Wound in this manner, there is no possibility of the nth turn coming in direct contact with a turn any farther removed from it than the ($n \pm 50$th). By winding and insulating the transformer in the manner described, it is estimated that the integrated effect of the 60-cycle current shunted from the primary winding has been reduced to less than 0.02 per cent of the total primary ampere-turns.

The importance of reducing the shunting effect of capacity between layers to this low value at 60 cycles, is realized when considering the magnitude of the effect for the higher harmonics, for example, the fifteenth. The capacity reactance between turns, layers and sections to the 15th harmonic is 1/15 of the reactance to 60 cycles; the impedance to the passage through the windings of the 15th harmonic in the current is approximately five times the impedance to 60 cycles; therefore, the percentage of the 15th harmonic shunted from the windings will be 75 times the percentage of the fundamental shunted.

If, then, less than 0.02 per cent of the 60-cycle current is shunted from the windings, the percentage of the 15th harmonic will be less than 1.5 per cent. The conclusion is that the influence of displacement currents within the primary winding may be neglected for the fundamental and any harmonic not higher than the 15th.

To check the preceding conclusions relating to higher harmonics in the current wave form, an oscillogram, Fig. 14,

(film 194) was taken with the connections shown in Fig. 15. In Fig. 15, *B* is a Leyden jar condenser having about 100 times the capacity of the condenser *C*, which consists of two concentric cylinders separated by air,—a steel wire 0.059 cm. in diameter in a 518-cm. length of pipe of 20.6 cm. diameter. Both condensers in parallel were connected across a high-tension transformer generating 9.6 kv. The charging current of the Leyden jars *B* was sent through the vibrator *P* and the charging current of the cylinder condenser *C* was sent through the primary of the current transformer, the secondary being connected to the vibrator *S*. The vibrator *E* shows the potential wave form across the primary of the transformer. The charging current of the two condensers *B* and *C* should have the same wave form, and any appreciable errors introduced by the transformer should cause an appreciable difference in

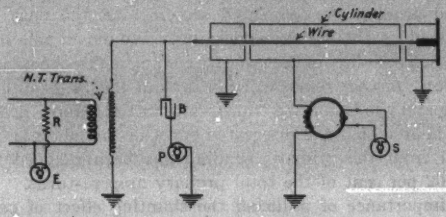


FIG. 15—CONNECTIONS TO SHOW THE REPRODUCTION OF HARMONICS

the shape of the current wave forms *P* and *S*. An examination of the oscillogram shows that the harmonics in the primary of the transformer are very faithfully reproduced in the secondary.

V. APPLICATIONS

The transformer extends the field of usefulness of the oscillograph by increasing a hundred fold its current sensibility. This makes it possible to use the oscillograph in fields from which it has hitherto been barred by reason of the minuteness of the currents to be studied. In this connection, however, it should be recalled that a current transformer cannot increase the watt sensibility of the oscillograph, and that the actual watt sensibility of the combined current transformer and oscillograph is thirty per cent of the watt sensibility of the oscillograph alone. Consequently, the current trans-

former can only be used where the current to be investigated flows under a voltage high as compared with the voltage consumed in the transformer. This voltage is of the order of ten volts for 0.0005 ampere. Figures 17 to 30 are oscillograms intended to show some of the applications of the combined current transformer and oscillograph.

Application to Corona Studies. The oscillograms, Fig. 17 to Fig. 21, (film 177 to 181), taken with the connections shown in Fig. 2, show the effect of corona formation on the charging current of a wire. The metal cylinder of Fig. 2 was an 8-in. (20.6-cm.) iron pipe 17 ft. (518 cm.) long, in the center of which was stretched a polished copper wire having a diameter of 0.227 cm. Corona is visible around this wire at 18.7 kv.

Fig. 17 (film 177) was taken at 17.8 kv.—below the voltage at which corona is visible.

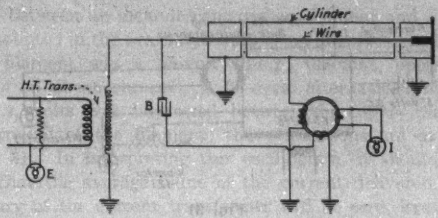


FIG. 16

Figs. 18 and 19 (films 178 and 179), were taken above the corona voltage at the voltages indicated on the films. They show: (a) the point on the e.m.f. wave form at which copious ionization sets in, (b) the duration of the period of ionization, (c) the asymmetrical nature of the process of breakdown. In all these films a positive current is a current from the pipe to the wire, or the wire is cathode for positive deflections.

The three films above referred to were taken with a combination of inductance and capacity in the circuit adjusted to "weed out" all harmonics from the generator wave form. The next two oscillograms, Figs. 20 and 21 (films 180 and 181), were taken with the same wire but without "weeding out" the harmonics from the impressed voltage.

To show more clearly the characteristics of the current which flows when corona forms, the connections shown in Fig. 16 may be used. In Fig. 16, the charging current from a con-

denser B, connected between wire and ground, is sent through one of the secondary coils of the current transformer in such a direction as to oppose the magnetomotive force of the primary current.

The capacity of the condenser B is adjusted so that its charging current neutralizes the charging current between wire and pipe for all voltages below the formation of corona. When corona forms, the two currents no longer balance, and the deflection of the current vibrator shows the current which is superimposed on the charging current as the result of the ionization. Figs. 22 and 23 (films 188 and 189), were taken with Fig. 16 connections, with a 0.059-cm. steel wire in the 8-in. pipe.

The asymmetrical nature of the current is more striking at low gas pressures than at atmospheric pressure. This is in-

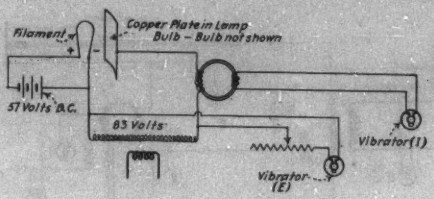


FIG. 31

dicated in Fig. 24, (film 224), an oscillogram obtained with a 0.102-cm. phosphor-bronze wire in the 8-in. pipe of Fig. 2.

This oscillogram was obtained with the pipe closed at the ends and exhausted to a pressure of 0.5 cm. of mercury.

Application to Insulator Investigations. The current transformer may be used to determine the charging and leakage currents of high-tension insulators and the ohmic resistance of wooden pins at high voltages.

With the connections shown in Fig. 1 the oscillograms in Figs. 25 to 29 were taken on a 10-in. (25.4-cm.) suspension insulator.

Figs. 25 and 26 (films 301 and 305) were taken at 18.2 kv., with the insulator dry and under spray, respectively. The spray was directed downward at an angle of 45 deg. from the vertical; the rate of precipitation was 0.6 in. (1.5 cm.) per minute. The 60-cycle charging current of the dry insulator at the rated voltage, eight kv., is 2.16×10^{-4} (r. m. s.) amperes, indicating a capacity of 3.14×10^{-11} farads. Under spray,

Fig. 26, the current leads the potential by only 70 deg., or the resistance of the insulator drops to 180 megohms.

Figs. 27 and 28 (films 304 and 308) show the charging current at a voltage high enough to cause streamers over a part of the insulator surface. The oscillograms were taken with the insulator dry at 38 kv. and under spray at 31.6 kv., respectively. For positive currents the insulator pin is cathode and the metal cap is anode.

Fig. 29 (film 307) is an oscillogram taken on a 10-in. (25.4-cm.) suspension insulator under spray, with the axis of the insulator horizontal. The insulator resistance is only seven megohms.

Application to the Study of Conduction in Gases. The transformer may be used to determine the wave form of the minute leakage currents between electrodes in gases at low pressures.

Fig. 30 (film 254) shows the wave form of the current through the gas between an incandescent carbon filament and a copper plate mounted in the evacuated bulb of an incandescent lamp.

The filament was a 55-volt 16-c.p. filament, operated at 57 volts on direct current. A 60-cycle alternating voltage of 83 r.m.s. volts was impressed between the copper plate and one terminal of the filament; the connections are as shown in Fig. 31. In interpreting this oscillogram, it should be recalled that the average value of the current delivered by the secondary of the current transformer will be zero, irrespective of the wave form of the primary current. The negative branch of the current wave does not mean that the primary current flows from the incandescent filament anode to the copper plate cathode. The primary current is unidirectional and only flows during the half-cycle in which the filament is cathode. No appreciable current flows when the cold copper plate is negative to the filament; the current shown by the oscillogram during this half-cycle is only an apparent current; it is due to the shift of the secondary current wave form with reference to the primary current wave. Both wave forms are similar, but the primary is unidirectional, while the average of the secondary must equal zero.

DISCUSSION ON "A MILLIAMPERE CURRENT TRANSFORMER" (BENNETT), WASHINGTON, D. C., APRIL 25, 1914.

J. B. Whitehead (by letter): In conjunction with Professor Bennett's paper* last year at Cooperstown, the present paper completes a description of the equipment with which he has obtained his interesting and valuable results on the corona. The transformer which he describes, by offering a means for measuring the corona current, should open up a wide field of investigation. The possibility, as demonstrated by Professor Bennett, of neutralizing the charging current is especially valuable.

One or two questions suggest themselves:

As the scale of the diagram for Fig. 5 is evidently not the same for all vectors, I have not been able to understand the statements at the top of the following page.

The statement is made on the next page thereafter, under the heading "Phase Displacement and Ratio of Transformation," that the phase displacement and percentage reduction in the multiplier are proportional to the secondary resistance. I shall be glad to have further elucidation here.

Referring to Fig. 15, since presumably all the vibrators were in one oscillograph, the question of potential difference arises, unless each vibrator was grounded.

J. R. Craighead (by letter): The specific features of design of a current transformer should be determined by the uses to which it is to be put. In Mr. Bennett's transformer, the primary winding is made of wire several times larger than would be needed on a heating basis, in order to keep the total impedance low. More accurate transformation of the current can be secured by using much smaller primary wire, thus increasing the ampere-turns or diminishing the mean length of magnetic circuit. This will be accompanied by an increase in the impedance and I^2R losses of the transformer which would be objectionable only for circuits of comparatively low voltage.

It should be emphasized that the current transformer is accurate only when carrying a true alternating current. When supplied with a current containing a direct-current component, it operates in a different range of flux density because of the constant magnetizing effect of the direct current, and the errors are largely increased. If a current transformer under normal conditions has from 2 to 5 per cent exciting current, the presence of a 50 per cent direct-current component therefore may readily give a direct magnetomotive force from 7 to 17 times as great as the maximum under operating conditions. Calculations of errors with alternating current alone cannot therefore be relied on to determine accuracy with pulsating

* "An Oscillograph Study of Corona", TRANS. A.I.E.E., Vol. XXXII, 1913, p. 1787.

currents. The alternating components of transients and rectified or partially rectified currents will not be accurately shown.

The alternative is the use of vibrators of higher current sensitivity. These are available of about 10 times the sensitivity of the standard vibrator, and consume about the same energy. This will cover satisfactorily many cases where the transformer would give inaccurate results, but will not reach to the extremely low values covered by the transformer.

Edward Bennett (by letter): With reference to the questions raised by Dr. Whitehead: In the vector diagram of Fig. 5 the exciting current I_e and its components I_m and I_w are drawn to ten times the scale of the primary and secondary currents. The voltage which must be generated by the magnetic flux in the iron, in order to set up the full load current through the secondary winding, will be directly proportional (approximately) to the total secondary resistance, since the reactance is negligible. The exciting current necessary in the primary to set up with magnetic flux will be approximately proportional to the flux and since the flux is proportional to the secondary resistance, therefore the exciting current will be directly proportional (approximately) to the total secondary resistance. An inspection of the diagram will show that the exciting current will remain less than 5 per cent of the neutralizing current I_n for a reasonable variation in the secondary resistance. Under these conditions a study of the diagram will show that since the exciting current is directly proportional to the total secondary resistance, therefore "for small variations in the resistance of the secondary circuit, the angle of phase displacement and the percentage reduction in the multiplier will be approximately proportional to the secondary resistance."

In Fig. 15 the terminal of vibrator P is grounded and the vibrator S is ungrounded. One terminal of the primary of the current transformer to which the vibrator S is connected is grounded and the average potential of the primary from ground is less than 6 volts, therefore the potential of the vibrator S will probably differ from ground potential by less than 2 volts.

Mr. Craighead's comments apply more particularly to the characteristics of instrument transformers in which flux densities from 500 to 2000 lines per square centimeter are in use. In the milliampere current transformer, in which the maximum flux density is only 36 lines per square centimeter, we encounter features of design that are entirely negligible in the commercial transformer. For example, very little improvement indeed can be made in the characteristics of the milliampere transformer by increasing the number of turns in the winding:

First: Because the permeability decreases rapidly for flux densities below 50 lines per square centimeter, so that very little is to be gained by using a lower flux density.

Second: Because an increase in the number of turns will increase to such an extent the component of the current which gets through the primary as displacement current from layer to layer, that high harmonics in the primary will not be faithfully reproduced.

Third: A material increase in the number of turns cannot be made without increasing either the length of the magnetic circuit or the resistance of the secondary.

Again, it would seem that the caution with reference to the use of the current transformer with pulsating currents can hardly be taken to imply that the oscillograms showing the presence of a large unidirectional component are appreciably in error. Even if the unidirectional component of the primary current exerted a magnetomotive force 17 times the exciting m.m.f., this would only lead to a unidirectional flux of 17 times 36, or 612 per square centimeter, on which would be superimposed a cyclic change of $\pm$ 36 lines per square centimeter. Under these conditions the wave form of the pulsating current would be faithfully reproduced in the secondary. As pointed out, however, in the paper, the wave form of the secondary current will, under these conditions, be so displaced with reference to the zero line as to make the average value of the secondary current zero.

Presented at the 294th meeting of the American Institute of Electrical Engineers, Washington, D.C., April 25, 1914, under the auspices of the Electrophysics Committee.

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THEORY OF THE CORONA

BY BERGEN DAVIS

ABSTRACT OF PAPER

The theory of the corona developed in this paper explains the coronal discharge by the application of the known laws of the discharge of electricity through gases.

The experiments of Dr. Whitehead and Mr. F. W. Peek and others have shown that the surface gradient X_s at the surface of a smooth wire necessary to start the corona increases very greatly as the radius of the wire decreases. As an illustration of this increase it is found that the coronal gradient X_s at the surface of a wire of 0.5 cm. radius is 46,000 volts per cm., while a gradient of 97,000 volts per cm. is required for a wire of 0.02 cm. radius. The phenomenon is due to ionization by impact. The ions n_0 move in toward the wire from the place at which they cross a region where the gradient is $X_0 = 26{,}600$ volts per cm. up to the wire. They produce other ions, and n ions arrive at the wire. The condition for the corona is that n shall be a constant. If α = the number of ions that one ion produces in a cm., then

$$n = n_0 \, e^{\int_a^b \alpha \, dx}$$

The α is a function of X at every point. This function is expressed in terms of x. It is introduced into the above equation, and on integration the equation for the corona is obtained. The equation also contains a term for the density of the air. The equation thus takes account of changes of pressure such as altitude and temperature effects. The equation when plotted in a curve for the variation of X_s with the radius of the wire, agrees with the experimental results of Whitehead and Peek with as great accuracy as the experimental results would warrant.

THE ATTENTION of the writer was first called to the coronal discharge from high-tension transmission lines by a paper presented to the American Institute of Electrical Engineers in 1911 by Prof. H. J. Ryan[1]. This discharge is a very interesting one from the point of view of the discharge of electricity through gases. The phenomena have been quite fully investigated and described by Dr. J. B. Whitehead, F. W. Peek and others.

When either a direct or an alternating high potential is applied to a smooth cylindrical conductor, there is at the surface of the wire a very high gradient of potential or electrical intensity.

1. TRANS. A. I. E. E., Vol. XXX., 1911, p. 1.

When this electrical intensity becomes great enough, the surrounding dielectric, in this case air, breaks down and a faint glow appears, and, as has been shown by Dr. Whitehead, the air becomes ionized. If the electrical intensity is still further increased, the ionization and luminosity increase also, and there is considerable loss of energy from the wire.

There are interesting relations between the surface gradients necessary to produce the corona and the radius of the wire. As the radius decreases, the electrical intensity increases very much, as is shown by the curves in Figs. 3 and 4. In a discussion of this effect Dr. Steinmetz has suggested that there is a skin effect at the surface of a conductor; that the dielectric strength of air is altered by contact with a curved metal surface. It appeared to the writer that this could not be the case, but rather that this phenomenon should be capable of explanation by the known laws of the discharge of electricity through gases. The following development of a theory of this effect appears to show that it is really a case of ionization by impact.

The theory of ionization by impact has been developed by Prof. J. S. Townsend. He has established by experiments, that if α is the number of new ions produced in a gas by one ion in going one centimeter when driven by an electrical intensity X, and p is the pressure of the gas, the following functional relation holds between α, x and p, for all values of α, x and p whatsoever:

$$\frac{\alpha}{p} = f\left(\frac{X}{p}\right) \tag{1}$$

When ionization by impact takes place in a gas, the density of ionization is enormously increased, as is shown by the following considerations. Let n_0 be the number of free negative ions crossing a unit of area of surface in a gas in unit time, under an electrical intensity X. Let α be the number of ions produced by one negative ion in going one centimeter.

If the ion moves a distance dx, the number produced will be $\alpha\, dx$, and if there are N such ions crossing any plane, the number crossing a plane dx distant will be $dN = \alpha\, N dx$. On integrating this between n_0 crossing plane of start of the action, and n, the number crossing a plane at distance d, we have:

$$\frac{n}{n_0} = \varepsilon^{\int_0^d \alpha\, dx} \tag{2}$$

If the electrical intensity is uniform between a and d, α is independent of x and the equation becomes

$$\frac{n}{n_0} = e^{\alpha d},$$ which is that used by Prof. Townsend.

The conditions about a cylindrical conductor may be described by use of the cross-section of such conductor represented by Fig. 1.

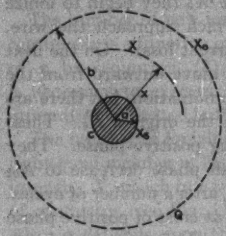

FIG. 1

The shaded portion c represents the conductor, whose radius is a. The electrical intensity at the surface of this conductor is X_s, and X represents the electrical intensity at any point distant x from the center of the conductor.

The cylindrical surface Q, whose radius is b, represents the surface where the electrical intensity has the constant value X_0. This electrical intensity X_0 is the least gradient of potential at which ionization by impact can occur. Ionization by impact and the coronal discharge itself can only take place between the surface Q and the wire, in which region the electrical intensity is greater than X_0.

Let E represent the potential difference between the wire and the ground or some other distant conductor, and let the distance of this other conductor or ground be R.

The electrical intensity at x is

$$X = \frac{E}{x \log \frac{R}{a}}$$

At surface it is

$$X_s = \frac{E}{a \log \frac{R}{a}}$$

At surface Q it is

$$X_0 = \frac{E}{b \log \frac{R}{a}}$$

From the above we obtain

$$X = X_0 \frac{b}{x}, \text{ and } X_s = X_0 \frac{b}{a}; \tag{3}$$

The physical process involved in the establishment of the discharge may be traced in the following way: The conductor is subject to an alternating potential. Let the maximum value of this at crest of the wave be just sufficient to produce the corona. There are a certain number of ions, N_0, in the region around the wire. Only negative ions ionize by impact at ordinary pressures. Suppose the wire to be at the positive phase, the N_0 ions move inward and when they cross the surface X_0 they begin to ionize by impact. They produce N_1 ions which approach the wire. Here some of the N_1 ions disappear (current loss). On the next phase, the wire is negative, these ions move outward from the wire. Some of them disappear by recombination, but there are N_{01} left, and N_{01} is much greater than the original N_0. These N_{01} ions move inward on the succeeding positive phase. They produce N_2 ions, which on the next half phase decrease to N_{02} ions, and thus the process goes on until, after a number of cycles, the density of ionization about the wire at crest of positive phase is n. The n_0 in the theory here proposed is the number of ions crossing the surface X_0 on the phase at which the discharge appears.

Now let n_0 be the number crossing the surface where the intensity is X_0, and let n be the number which reach the surface of the wire, and assume also that the visible discharge appears when n reaches a fixed constant value.

From equation (2),

$$\frac{n}{n_0} = e^{\int_a^b \alpha\, dx} \tag{4}$$

The density of ionization at surface of conductor will increase somewhat, without ionization by impact, as the N_0 ions move inward. This increase will be proportional to the ratio of the radius of surface Q to that of the conductor.

We may now write

$$\left(\frac{n}{n_0}\,\frac{a}{b}\right) = e^{\int_a^b \alpha\, dx} \tag{5}$$

One may assume that the discharge will appear when the ionization per unit area at the surface reaches a certain constant value n.

An inspection of Fig. 1 will also show that the number of n_0

ions, crossing surface Q per unit area, varies inversely as b; consequently, we may approximately assume that the whole term on the left is a constant for first appearance of discharge.

$$\text{Constant} = \left(\frac{n}{n_0}\ \frac{a}{b}\right) = e^{\int_a^b \alpha\, dx} \tag{6}$$

The number of new ions α that one ion produces in going one centimeter is a function of X, by equation (**1**), and X is a function of x by equation (**3**), so that α is a function of x. It is necessary to express this function in order to perform the integration indicated in the right-hand member of equation (**6**).

The number of ionizing impacts per cm. indicated by α in the right-hand member of (**6**) depends upon the value of the electrical intensity X, which in turn depends on the distance x from center of conductor (see Fig. 1). Consequently, α will depend upon x. Also, α depends upon the pressure of the air.

Since we find that α is a function of x and p, it is necessary to express the form of this functional relation.

A few years ago, the writer[2] developed a theory of ionization by impact, by means of which the form of the function

$$\frac{a}{p} = f\left(\frac{X}{p}\right), \text{ may be expressed.}$$

The complete development of this function cannot be given here, but the reader is referred to the original paper.

The expression there obtained for α is

$$\alpha l = e^{-\frac{\lambda_0}{l}} + \frac{\lambda_0}{l} E i\left(-\frac{\lambda_0}{l}\right) \tag{7}$$

where λ_0 is the least ionizing path of an ion when driven by a field X, and l is the mean free path of the negative ion at the pressure considered. The least possible difference of potential through which an ion must freely run to produce ionization is $v = X\lambda_0$. The quantity $X\lambda_0$ should be a constant for any gas, independent of the pressure and independent of the electrical intensity.

2. *Physical Review*, Jan. 1907, also *Annalen der Physik*, Band 42, 1913.

Recent experiments by Bishop[3] show this to be the case, and the value he finds for v in case of air is $v = 10.2$ volts.

Equation (7) very easily transforms into the following expression:

$$\frac{\alpha}{p} = \frac{1}{76\,L}\left[e^{-\frac{v}{76\,L}\frac{p}{X}} + \frac{v}{76\,L}\frac{p}{X}\,Ei\left(-\frac{v}{76\,L}\frac{p}{X}\right)\right] \quad (8)$$

where $v = X\lambda_0$, p is the pressure of the air in cm. of mercury, and L is the mean free path of an ion at normal pressure.

The above equation expresses the form of the function

$$\frac{\alpha}{p} = f\left(\frac{X}{p}\right)$$

If the value of α from this expression is introduced into equation (6), and likewise the values of X in terms of x are introduced from (3), we will have a complete expression for the appearance of the corona, at any pressure and for any size of conductor. However, equation (8) is not directly integrable for x. It contains the exponential integral

$$Ei\left(-\frac{v}{76\,L}\cdot\frac{p}{X}\right)$$

which is a series, every term of which would need to be separately integrated, for every case. This equation is consequently unworkable.

An integral equation which is a close approximation to (8) must be found. Equation (9) is such an expression. Its departures do not introduce any considerable errors, particularly for values of $\frac{X}{p}$ less than 900.

The approximate equation is

$$\frac{\alpha}{p} = A + B\left(\frac{X}{p} - 350\right)^2 \quad (9)$$

If the constants A and B are given the values 0.05 and 0.0000115 respectively, a good agreement of (9) and (8) is obtained, as shown by the curves in Fig. 2.

3. *Physical Review*, Nov. 1911.

By setting $X_0 = 350\ p = 26{,}600$ volts per cm., equation (**9**) becomes

$$\alpha = A\ p + B\ \frac{p}{p^2}\left(X - X_0\right)^2$$

Also, from equation (**3**), the above becomes

$$\alpha = A\ p + B\ p\ \frac{X_0^2}{p^2}\left(\frac{b}{x} - 1\right)^2 \tag{10}$$

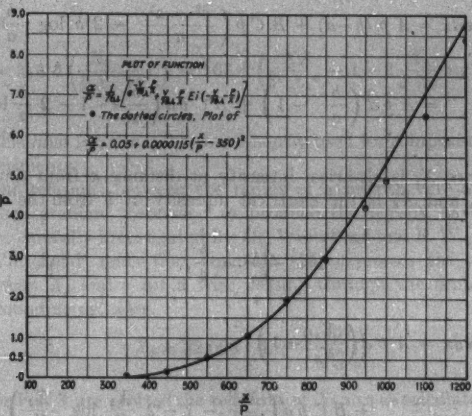

FIG. 2

It is to be noted that X_0 is the electrical intensity at points indicated by the dotted circle Q in Fig. 1. It is the least gradient at which ionization by impact can occur. Also X_0 depends on the pressure in such a way that $\frac{X_0^2}{p^2} = C$ is a constant independent of the pressure. It has the numerical value $(350)^2 = 122{,}500$ volts per cm.

Equation (**10**) becomes

$$\alpha = A\ p + B\ C\ p\left(\frac{b}{x} - 1\right)^2 \tag{11}$$

This expression for α is introduced into equation (**6**)

$$\int_a^b \alpha\, dx = A\, p \int_a^b dx + B\, C\, p \int_a^b \left(\frac{b}{x} - 1\right)^2 dx$$

The limits of integration are a and b, since the ionization takes place as the ions move inward from the surface of radius b to the surface of the wire of radius a.

Performing the indicated integration,

$$\int_a^b \alpha\, dx = A\, p\, (b-a) + B\, C\, p \left(\frac{b^2 - a^2}{a} - 2\, b \log \frac{b}{a}\right)$$

$$= A\, p\, a \left(\frac{b}{a} - 1\right) + B\, C\, p\, a \left(\frac{b^2}{a^2} - 1 - 2\, \frac{b}{a} \log \frac{b}{a}\right)$$

Since X_s is electrical intensity at distance a from center of wire, and X_0 is the electrical intensity at b from the center,

$$\frac{X_s}{X_0} = \frac{b}{a},$$

$$\int_a^b \alpha\, dx = A\, p\, a \left(\frac{X_s}{X_0} - 1\right)$$

$$+ B\, C\, p\, a \left(\frac{X_s^2}{X_0^2} - 1 - 2\, \frac{X_s}{X_0} \log \frac{X_s}{X_0}\right) \quad (\mathbf{12})$$

It is desirable to introduce into the above a term representing the density δ of the air, where δ = unity for p = 76 cm.

Also note that $\delta\, X_0$ expresses the value of the least gradient at which ionization takes place for any density δ of the air.

Equation (**12**) now becomes

$$\int_a^b \alpha\, dx = 76\, A\, a\, \delta \left(\frac{X_s}{\delta\, X_0} - 1\right)$$

$$+ 76\, B\, C\, a\, \delta \left(\frac{X_s^2}{\delta^2\, X_0^2} - 1 - 2\, \frac{X_s}{\delta\, X_0} \log \frac{X_s}{\delta\, X_0}\right)$$

Upon introducing the values of the constants A, B and C, equation (6) becomes

$$\left(\frac{n}{n_0}\frac{a}{b}\right) = e^{3.8\,a\,\delta\left(\frac{X_s}{\delta X_0}-1\right)+107\,a\,\delta\left(\frac{X_s^2}{\delta^2 X_0^2}-1-2\frac{X_s}{\delta X_0}\log\frac{X_s}{\delta X_0}\right)} \quad (13)$$

The above is a general expression for the relation between the gradient X_s and the radius a of the wire for conditions necessary to produce the corona.

Writing the above in the logarithmic form, and since the left-hand member is constant, setting $\log\left(\frac{n}{n_0}\frac{a}{b}\right) = K$, one obtains

$$\frac{K}{a} = 3.8\,\delta\left(\frac{X_s}{\delta X_0}-1\right)+107\,\delta\left(\frac{X_s^2}{\delta^2 X_0^2}-1-2\frac{X_s}{\delta X_0}\log\frac{X_s}{\delta X_0}\right) \quad (14)$$

This final form may be conveniently used for comparison with experiments.

The relations between the radius of a smooth wire and the surface gradient necessary to produce the corona have been quite carefully investigated by Dr. Whitehead and F. W. Peek.

Whitehead[4] finds that equation (15) expresses the relation between X_s and a for a wire passing through the center of a surrounding cylinder.

$$X_s = 32{,}000\left(1+\frac{0.297}{\sqrt{a}}\right) \quad (15)$$

In Fig. 3 are plotted the relations of X_s to a as calculated from (14). The constant $K = 6$ is found by equating (14) with (15) for a particular value for X_s and a.

The dotted circles represent the results of experiment as expressed by the empirical equation (15). The agreement between theory and experiment is very satisfactory.

F. W. Peek[5] has investigated the problem for parallel wires in the open air. He also investigated the effect of spacing of the parallel wires. He finds that if the conductors are not too near, the relations between radius and surface gradient may be expressed by

$$X_s = 29{,}800\left(1+\frac{0.301}{\sqrt{a}}\right) \quad (16)$$

4. Trans. A. I. E. E., Vol. XXX, 1911.
5. *ibid.*

The law of the corona for this case is the same as for a wire enclosed in a cylinder, but the electrical intensity at which it occurs is less than for the enclosed wire, as the constant outside the parentheses has a smaller value.

The theoretical equation represents this case also. The constant K has a smaller value, as the constant outside the parentheses in (**16**) is less than that in (**15**). The comparison of theory and experiment is shown in Fig. 4. The agreement here also is very good.

Reduction of Equation (14) to Form of Equation (15)

The fact that equations (**14**) and (**15**) plot into almost identical curves is evidence that the theoretical equation expresses

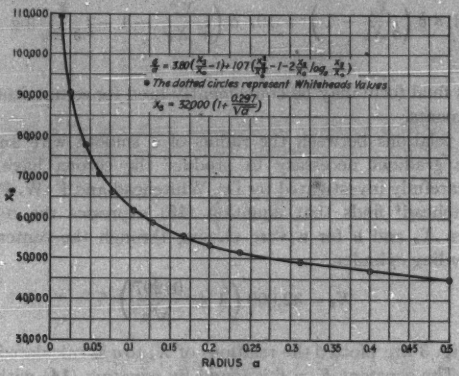

Fig. 3

the law of the corona as accurately as the empirical equations of Dr. Whitehead and Mr. Peek. However, equation (**14**) is not quite so workable in practise since it is not so simple in form and contains a logarithmic term. It is perhaps worth while to show that equation (**14**) very easily transforms into equation (**15**) if one represents the logarithmic term by a series:

$$\log_e \frac{X_g}{X_0} = C_1 \frac{X_g}{X_0} + C_2 \frac{X_0}{X_g} + C_3$$

This logarithmic term is very closely represented by the series if one gives the constants the values of 0.28, −0.82 and 0.53,

respectively. Introducing these values of C_1, C_2 and C_3 in the series, substituting the series for the logarithmic term of (**14**), and collecting the constants of like powers of $\frac{X_s}{X_0}$, equation(**14**) immediately changes to

$$X_s = 32{,}000\left(1 + \frac{0.297}{\sqrt{a}}\right)$$

This simple transformation makes (**14**) agree in form and value with the experimental equation of Dr. Whitehead.

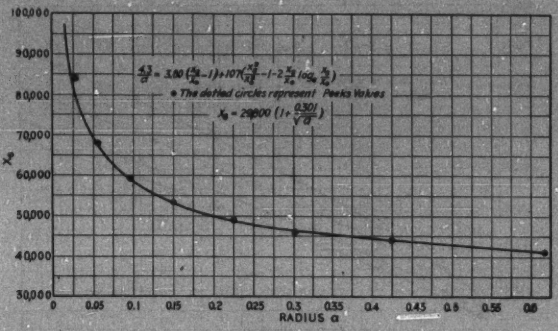

FIG. 4

CHANGE OF DENSITY OF THE AIR

Both Dr. Whitehead and Mr. Peek have investigated the effects of pressure or density of the air on the appearance of the corona. Peek points out that both his own and Whitehead's results may be represented by the following empirical equation:

$$X_s = 31{,}000\,\delta\left(1 + \frac{0.308}{\sqrt{\delta a}}\right) \qquad (17)$$

The term δ represents the density of the air, taking δ = unity for normal atmospheric pressure and temperature. Equation (**14**) also contains δ and consequently should also express the effect of change of density.

A plot of (**14**) is given in Fig. 5 for a few conductors of different radii, the dotted circles representing the results of experiments. Here again the agreement is very good.

Conductors Surrounded by Cylinders, and Conductors in the Open

There is a marked increase in the surface gradient required to produce the corona with the wire surrounded by a cylinder over that of a wire in the open. The experimental values of X_s are about 7 per cent greater in the one case than in the other. The theory of ionization by impact furnishes an explanation of

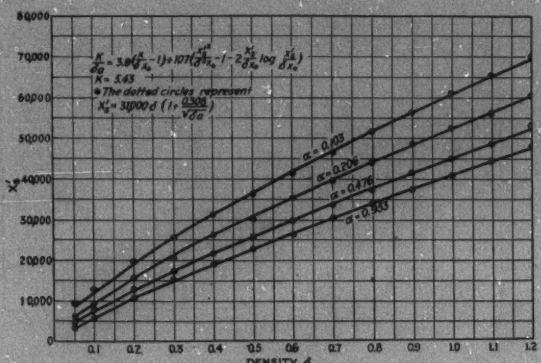

Fig. 5

this increase, as will be readily seen by a detailed study of the physical process involved in the two cases.

Consider a wire stretched through the center of a metallic cylinder, as represented in Fig. 6. The outer cylinder M, say, has a radius of 3 to 5 cm., these being the dimensions used by Dr. Whitehead. The central conductor is charged by an alternating potential, such that the gradient at the surface just produces the corona. The condition for the discharge is that the ionization n per unit area at the surface shall reach a certain value. Assume a certain amount of ionization in the cylinder, and follow the process through a cycle. The wire is just beginning its negative phase, and as the potential rises, the negative ions

are driven out from the wire toward the outer cylinder. If the radius R is small, these ions will reach the outer cylinder M and disappear before the wire changes to the positive phase. If the outer cylinder M is not there, but another wire or the earth is at a considerable distance, the ions will not have disappeared, but will still exist and many will return and cross the surface Q, on the reversal of phase. The n_0 ions of equation (**13**) are thus decreased by the nearness of the cylinder, and the gradient X_s is increased. One can readily calculate the change in n_0. For a wire in the open (see Fig. 4):

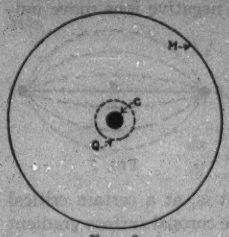

FIG. 6

$$K = \log\left(\frac{n}{n_0}\,\frac{a}{b}\right) = 4.3$$

And for a wire in a cylinder (see Fig. 3):

$$K = \log\left(\frac{n}{n_0}\,\frac{a}{b}\right) = 6$$

The ratio of a to b will be about the same in the two cases. It is found from the two expressions above that n_0 is 5.5 times as great for a wire in the open as for a wire enclosed in a cylinder.

THE EFFECT OF SPACING OF PARALLEL CONDUCTORS

Mr. Peek has observed some interesting and unexpected results of the effect of spacing of parallel conductors. It was found that at great distances, a change in spacing had no effect on the coronal surface gradient, but when the wires were brought nearer, the gradient increased, and at a certain spacing not near enough for sparking, the gradient became nearly as great as for wires surrounded by a cylinder. As an illustration, when the two parallel conductors of 0.1 cm. radius are 20 cm. apart, the gradient is 58,000 volts per cm.; when they are 7 cm. apart, the coronal gradient is increased to 61,000 volts per cm.

These results can also be explained by the assumption that part of the n_0 ions disappear when the conductors are near.

Consider the physical process about conductor C, Fig. 7, as the

potential goes through a cycle. The conductor C begins with a negative potential which increases, decreases, and becomes positive. During the negative phase, the negative ions move outward along the lines of force towards B. If the conductors are sufficiently far apart, these ions will not reach B before the phase changes and they are again drawn toward C. However, if the spacing d is small enough, some of the n_0 ions will have reached B and so will have disappeared. That is, at a certain critical spacing n_0 will begin to decrease, and the coronal surface gradient will begin to increase.

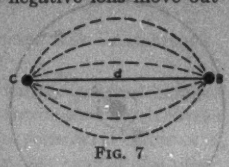

FIG. 7

This increase in X_s is shown by several curves in Peek's paper. The critical spacing at which this increase in X_s takes place is given in the following table (d observed).

a	X_s	d (observed)	$d = c\sqrt{X_s a}$
0.103	58,000	17 to 18 cm.	17.5
0.162	52,500	18 to 21	21.
0.2	50,000	21 to 23	23.
0.327	46,000	28 to 31	28.
0.412	44,000	32 to 34	32.

$c = 0.23$ = a constant.

The change in the gradient as the spacing is decreased is so gradual that the critical spacing d at which X_s begins to be increased cannot be sharply fixed.

The expression in the fourth column of the table for the critical spacing is derived from the following considerations: This spacing is the distance that an ion would move out from conductor C in a quarter-cycle. All of those ions that are to cross the surface X_0 at the crest of the positive wave, must be within such distance of the wire, that they can return while the potential is increasing from zero to a maximum on the positive phase.

Let k be the specific velocity of an ion, and X the gradient at a point x at a time t. Then $k X$ will be the velocity at that point and time.

$$\frac{dx}{dt} = k X$$

and $$X = X_s' \frac{a}{x}$$

Also

X_s' varies with the time.

$$X_s' = X_s \sin p\,t$$

$$\frac{dx}{dt} = k\,X_s \frac{a}{x} \sin p\,t$$

$$\int_a^d x\,dx = k\,X_s \frac{a}{x} \int_0^{\frac{T}{4}} \sin pt\,dt$$

$$d^2 - a^2 = \frac{k\,X_s\,a}{\pi f}$$

Since a is very small compared to d, it may be neglected, and setting

$$c = \sqrt{\frac{k}{\pi f}} = \text{a constant}$$

the above becomes

$$d = c\sqrt{X_s\,a} \tag{18}$$

which is the equation by which the fourth column of the table is calculated.

The Nature of the n_0 Ions

The theory here proposed for the corona is founded upon the assumption that there is a large number of ions n_0 which cross the surface X_0 and build up the ionization to n ions at the surface of the wire, while the gradient is near its maximum on the positive phase.

This foundation principle seems to be opposed by some experiments of Dr. Whitehead[6]. This contradiction, however, is only apparent. It is perhaps worth while to give his work in more detail and show that this is the case.

(a) An effect was sought for by increasing the original ionization about the wire by ionizing the air about the wire within

6. Trans. A. I. E. E., Vol. XXXI, 1912.

the cylinder by Röntgen rays. The result was negative; no change in the coronal voltage was observed.

(b) The wire is surrounded by thin paper tubes within the cylinder. "A clean copper wire 0.157 cm. in diameter, started the corona at 58.5 primary volts. This wire was then successively enclosed in thin paper tubes 2.54 cm., 1.27 cm. and 0.95 cm. in diameter. These tubes were slightly longer than the outer cylinder and were insulated and held accurately concentric by means of three threads at each end".

"Ions in the region outside of these tubes would be prevented from reaching the wire, and if these ions have any influence on the coronal voltage, we should expect an elevation of this voltage, when the wire is screened as above. No change in the coronal voltage was observed when the larger tube was in place. In the case of the smaller tubes the coronal voltage (primary) was lower, by 1.5 to 2 volts, than when the tubes were not inserted. In this experiment, the number of ions in the neighborhood of the wire is lower when the paper tube is in place."

A closer examination of the physical process about the wire will show, however, that neither the Röntgen rays nor the paper tubes can have much effect on the number of the n_0 ions considered in this theory.

Suppose that the alternating potential applied to the wire for experiment (a) is such that the surface gradient will just produce the corona.

For the sake of clearness, consider that the potential is applied to the wire at the beginning of the positive phase. The ions present, due to the natural ionization of the air, move inward toward the wire, and designate by N_0 those that cross the surface X_0 at crest of positive phase. These produce ionization by impact and N_1 ions arrive at the wire, (see Fig. 8). These N_1 ions are not numerous enough, however, to produce a visible corona. Some of these N ions are neutralized by the wire (current loss), and on the next phase, when the wire is negative, the remainder move outward, passing the positive ions which are moving inward. Many disappear by recombination during this time, but a number much greater than the original N_0 is left. On the next change to the positive phase, N_{01} ions cross the surface X_0 at crest of wave. These produce N_2 ions which arrive at the surface of the wire. Part of these ions disappear as before, but leave N_{02} ions for the next process. Thus the ionization builds up in a manner graph-

ically shown in Fig. 8. The n_0 ions of the theory and of Fig. 8 are many thousand times more numerous than the original N_0 which are due to the natural ionization of the air.

The Röntgen rays as applied by Dr. Whitehead would increase the N_0 ions, but not the n_0 ions. But the number of cycles required to build up the ionization would be decreased by the application of the Röntgen rays.

This process requires that a number of cycles should elapse between the application of the potential to the wire and the appearance of the corona. I venture to predict that such delay would be observed if the experiment were performed in the following way. The potential of the secondary should be adjusted so as

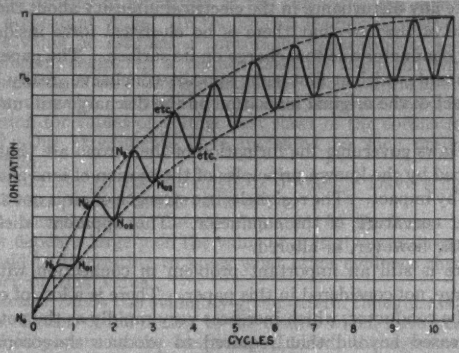

FIG. 8

just to produce the corona. A suitable switch should be placed in the secondary circuit. The current in the primary should be kept on continuously. The coronal discharge should appear many cycles after the closing of the switch in the secondary. This arrangement avoids the sudden rush of current into the transformer on closing the primary switch.

Such an effect has been observed. A graduate student, working under the direction of the writer at the Physical Laboratories of Columbia University, obtained such nice adjustment of potential difference that the discharge would regularly appear three minutes after the application of the potential to the electrodes. Here, the rate of production only slightly exceeded the

rate of disappearance of the ions. It took a long while to build up from N_0 to n ions.

The above view of the physical process about the wire also explains the absence of any considerable effects when the wire is inclosed in a paper tube. The building-up process at successive cycles indicated in Fig. 8, goes on inside the paper tube. As the wire is on successive negative phases, the N_{01}, N_{02}, N_{03} etc. ions are driven outward and cling to the inside wall of the paper tube. As the wire changes to the successive positive phases, these N_{01}, N_{02}, N_{03} ions come free from the wall of the tube, and move inward, producing ionization by impact in the same way as though the paper tube had not been there.

The negative ions while on the inner wall of the tube will not produce any disturbance in the electrical intensity about the wire, because of the law that there is no electrical force inside of a hollow conductor due to a charge on its surface. The paper tube experiment, which at first sight appears conclusive, really leaves the effect of the original ionization on the discharge still undetermined.

The laws governing the formation of the corona are thus fully explained by the known principles of the motion of ions and ionization by impact. The real dielectric strength of air is not altered by the curvature of the conductor. The apparent dielectric strength, however, is altered.

There is still an important problem in connection with the discharge, not considered in this paper. There is a loss of energy from the conductor, which increases very rapidly as the potential is increased beyond that required to produce the corona. It would be desirable to develop a theory that would completely describe this energy loss in terms of ionization by impact. However, new and great difficulties are encountered when this is attempted. The redistribution of the ions causes a modification of the electric field about the conductor. The representation of this new field distribution in terms of the ionic charges and their motions, by a differential equation, is a matter of very great difficulty.

DISCUSSION ON "THEORY OF THE CORONA" (DAVIS), WASHINGTON, D. C., APRIL 25, 1914.

J. B. Whitehead (by letter): Professor Davis's paper is noteworthy as being the first thorough-going attempt to explain the phenomena of corona formation in terms of the theory of ionization. In each of the papers of my series on *The Electric Strength of Air*, I have stated my opinion that the phenomena in question would ultimately be explained in terms of that theory. Professor Davis is the first, however, to offer to the Institute a theory which begins from the fundamental relations given by Professor J. S. Townsend, the originator of the theory of ionization by collision, as the explanation of all electric discharges in gases. Professor Davis makes a number of assumptions which will require careful investigation before acceptance. Among these is that which states as the critical condition for corona formation that the density of ionization at the surface of the wire should reach a constant value. In the process leading up to the arrival at this value he assumes a continuous generation of new ions by collision, beginning a certain distance from the wire and accumulating in time through successive cycles of the alternating electric intensity. If this is true, should there not be evidence of ionization for values of voltage just short of the corona-forming value? Our experiments have indicated no such preliminary ionization.

I should like to ask the origin of Professor Davis's figure of 26,000 volts per cm. as the value of X_0.

The correctness of the development of Professor Davis's theory depends largely on the value of α as given in formula (7). It would be interesting to know what other evidence there is in support of this value.

Professor Davis has evidently given careful thought and study to the relation of his theory to the results which have been presented in papers to the Institute. Indeed, the agreement between the theory and observations is so remarkable that it is to be hoped that Professor Davis will in a further paper discuss the possible errors introduced by several assumptions which he has made in the reasoning. I have not found it possible to check them all.

It may be well to point out that Professor Townsend has himself offered an explanation of the relation obtaining between the critical corona intensity, the diameter of the wire and the density of the gas, in an article in the London *Electrician* for June 6, 1913.

Harris J. Ryan (by letter): The Davis theory of corona presents for the first time a definite and satisfactory correlation of the essential factors that cause corona formation on high-voltage transmission lines. The theory has not been extended, as yet, so as to account fully for *local corona* that generally precedes full corona formation, and for the strength of the corona-formed

ionic (in phase) current in relation to frequency and voltage. This does not lessen its integrity nor its value. Merely its opportunity for growth is thus emphasized and such growth will be sturdy. In due course of time it will be extended so as to account for most if not all of the corona phenomena.

The author's fundamental assumptions in regard to the dual origin of the n_0 ions and the corona-culminating role of the n ions are made upon firm ground. Assumptions employed in the construction of a satisfactory theory must be nominated by corresponding facts. The Columbia University experiment which demonstrated the time-lag of the arrival of the initial corona has contributed an important nominating fact in regard to the n_0 ions. We have found in our own work that the normal critical visual corona-forming voltage applied to parallel wires may be lowered greatly, as much as fifty per cent, by liberating near such wires an independent supply of ions. This was done by mounting a fine wire between the high-voltage wires and charging it from a static machine. Objection to this experiment was made on the ground that the electric field about the high-voltage wires is increased by the presence of the charged fine wire. So it is, but the increase is far too little to account for the results. This has been demonstrated by computation and experiment. The results of the experiment fortify the author's assumptions that corona formation is dependent upon the initial supply of free ions, N_0, and "that the discharge will appear when the ionization per unit area at the surface reaches a certain constant value, n." Also that "the density of ionization at the surface of the conductor will increase somewhat without ionization by impact as the N_0 ions move inward."

We have been working during the past two years with a steady, undamped, high-frequency, high-voltage source and have observed that coronas formed at 60,000 cycles per second consume large amounts of power and develop correspondingly high temperatures. These corona temperature effects continue to increase with frequency increase. The highest frequency used has been 600,000 cycles. The values of such steady high-frequency high voltages required to discharge across sphere gaps are much the same as the corresponding values at low frequencies. The corresponding voltages required to discharge through corona-forming blunt-pointed gaps are generally about one-half those required at low frequencies. Large, vigorous, local high-frequency corona brushes are formed on slight provocation at abnormally low voltages. A brush of this character may be blown by lung power from the point of the circuit where it originated to another point whereat it could not be started by the unaided action of the circuit supplied by a given voltage. These corona brushes may also be started at sub-critical voltages by touching the circuit momentarily with a stick of wood. The corona brush will start at the spot on the conductor touched by the wood. In these high-frequency phenomena we have much evidence of

the correctness of the author's implied assumption that the number of ions maintained in action, producing in-phase current, depends upon the shortness of their amplitudes of actual travel and of intervals of replenishment, *i.e.*, upon the frequency of the source.

Edward Bennett (by letter): The paper on the *Theory of Corona* contains a derivation from rational considerations of an equation which fits certain curves experimentally determined by Peek, Whitehead and others. These curves show the relation between the radius of wires of different diameters and the hypothetical gradients at the surface of the wires which cause ionization of the surrounding air to become evident.

The justification for some of the rational notions made use of by the author is not at all clear to me, while other assumptions do not seem to be in accord with the interpretation to be placed upon the experimental data. For example, it seems to be assumed that ionization will first be evident during that half-cycle of the alternating wave in which the electrons are moving inward across the surface Q of Fig. 1 toward the surface of the wire. Now, oscillograms taken at air pressures in the neighborhood of one cm. of mercury show that as one gradually raises the voltage between wire and surrounding cylinder, there is quite a range in voltage during which copious ionization occurs only during the half-cycle in which the wire is cathode, or the electrons move outward. At atmospheric pressure it is impossible to tell from the oscillograms the polarities under which copious ionization sets in. That is, as one slowly raises the voltage between the wire and surrounding cylinder the oscillograph gives evidence of ionization at substantially the same impressed voltage at which the eye sees the bluish haze around the wire. In addition the oscillograph also shows that ionization is occurring not only during the half-cycle in which the wire is positive but also during the half-cycle in which the wire is negative to the cylinder. This would seem to indicate that ionization resulting from both positive and negative ions should receive consideration in any derivation of the relation between the critical gradient and the radius of the conductor.

Referring to equations (**5**) and (**6**) the author makes the statement: "An inspection of Fig. 1 will show that the number of n_0 ions, crossing the surface Q per unit area, varies inversely as b; consequently, we may approximately assume that the whole term on the left is a constant for first appearance of discharge." It is not clear to me either why n_0 varies inversely as b, or why the left member of equation (**6**) may be regarded as approximately constant, and it would be gratifying if the author would elaborate on these two assumptions.

Alex. Chernyshoff (by letter): Mr. Davis and Prof. Townsend in their work have taken into account only the kinetic energy of the electrons and positive ions, leaving entirely out of consideration the possibility of the influence of the electric field on the

molecules themselves. Under action of the electric field the inner cohesion between the electrons and positive ions may be weakened within the neutral molecule. In consequence of this weakening, a smaller amount of kinetic energy will be required for the process of ionization. The inner cohesion between the positive and negative ions varies with the nature of the gas. In some cases the effect of this degree of cohesion may be considerable. The exception presented by helium seems to be especially interesting. The density of helium is double that of hydrogen. The average free path in hydrogen ought, therefore, to be twice as long as in helium. In accordance with Prof. Townsend's theory, it is necessary to assume that the negative ion comes twice as many times in collision (5:2.4) passing through a certain space in hydrogen as it does in helium under the same pressure. Is it not reasonable to conclude that this exception is due to the influence of the field on the neutral molecule itself?

For the further elucidation of my explanation let us consider the following: Let us suppose that we have to do with a gas having no free ions and from which all ionizing influences are removed. When acted upon by a high voltage, theoretically there ought not to be any discharge produced in that gas, no matter how high the tension may be. Of course, it is hardly possible to be certain in concrete cases that all sources of outside ionization are actually absent, in view of the omnipresence of radioactive substances, but if all such substances were removed a certain tension higher than usual would produce a discharge in the gas.

It seems to me that in considering the question of the causes of the appearance of corona, it is necessary to take into account the influence of the field.

In the second statement of the author, when pointing out the interdependence between the diameter of the conductor and the surface gradient necessary for the appearance of corona, it was assumed that the field had a logarithmic distribution, *i. e.*, the absence of free electricity between the conductor and the cylinder or the earth was assumed. In some cases, for instance, when the distance between the cylinder and conductor is small, this assumption, perhaps, does not introduce any significant error. But as soon as the diameter of the cylinder reaches the dimension of 40 cm., the discrepancies in the distribution of the field, as pointed out by Starke, may reach 10 per cent even in the most simple case. When the distance is larger, the effect on the distribution will be still greater. In view of the complexity of the problem in the case of alternating currents, I will point out here the dependence between the gradient of the field and the constant of the ionization and the diameter of the cylinder, for a constant electric field and when the ionization is not caused by collision but is caused by the influence of an outside force. If we indicate the number of ions on each square cm. of the surface of the conductor during one second by N, the density of current by i, the density of free electricity near the surface of the conductor

by ρ, the difference of the potential between the cylinder and the conductor by V, by D and a the diameters of the cylinder and conductor respectively, by e the charge of the ion and by x its mobility, we will get for the density of the current i the following formula:

$$i = \rho x \frac{dV}{dz} = Ne$$

Applying the equation of Poisson to cylindrical coordinates

$$\frac{\delta^2 V}{\delta z^2} + \frac{1}{z}\frac{\delta V}{\delta z} + \frac{1}{z^2}\frac{\delta^2 V}{\delta \varphi^2} + \frac{\delta^2 V}{\delta z^2} = -4\pi\rho$$

For the given case the equation is

$$\frac{\delta^2 V}{\delta z^2} + \frac{1}{z}\frac{\delta V}{\delta z} = -4\pi\rho$$

or by substituting the value for ρ

$$-\frac{N}{x\frac{\delta V}{\delta z}} = \frac{1}{4\pi e}\left(\frac{1}{z}\frac{\delta V}{\delta z} + \frac{\delta^2 V}{\delta z^2}\right)$$

$$-\frac{4N\pi e}{x} = \frac{1}{z}\left(\frac{\delta V}{\delta z}\right)^2 + \frac{\delta^2 V}{\delta z^2}\frac{\delta V}{\delta z} = \frac{1}{z}\left(\frac{\delta V}{\delta z}\right)^2 + \frac{1}{2}\frac{\delta\left(\frac{\delta V}{\delta z}\right)^2}{\delta z}$$

The integration of this equation will give

$$\left(\frac{\delta V}{\delta z}\right)^2 = -\frac{8\pi}{3}\frac{eNz}{x} + \frac{C}{z^2}, \text{ or}$$

$$\frac{\delta V}{\delta z} = \sqrt{-Az + \frac{C}{z^2}}$$

where

$$A = \frac{8\pi}{3}\frac{eN}{x} = \text{const.}$$

Neglecting the first member under the radical, we will get the logarithmic distribution of the electric force, for

$$C = \frac{V}{\log\left(\frac{D}{a}\right)}$$

The first member will gain more and more in significance as the diameter of the cylinder increases.

When the potential is alternating or variable the phenomena will be very much more complicated and it will not be possible to integrate the differential equation and in this way determine fundamental dependence of the gradient from the diameter of the cylinder and the constant of ionization, but this increased complexity of the phenomena does not change their essential character. I therefore think that when the distance between the earth and the conductor is considerable the variation of the field distribution of potential from the logarithmic curve will be considerable. In the case of ionization through collision there will be an enhanced inequality in the distribution of free electricity due to the difference in mobility of various ions.

In conclusion I want to relate one very interesting experiment demonstrating the action of light on electric discharges. Lebedinsky proved that light can not only facilitate the appearance of an electric discharge in the shape of a spark between electrodes, but that under certain conditions it may check its appearance. The experiment was conducted as follows:

A variable tension was placed near the breakdown. A slight illumination of one of the unsymmetrical electrodes regularly produced the appearance of a spark discharge. When the illumination was strengthened, irregular discharges were produced, and with a stronger illumination the discharges were discontinued entirely, while there was no change in the tension between electrodes. The reason for this phenomenon is the increased number of negative ions changing the distribution of potential in such a way as to prevent a discharge. This phenomenon, viewed from our point, demonstrates the importance of the field distribution and the dependence of the distribution of the free ions in the gas.

F. W. Peek, Jr. (by letter): It may be of interest to state, in a brief way, the manner in which our law of visual corona was derived, and also to call attention to the fact that it is a rational law. In 1910 I conducted an investigation, very carefully determining the visual corona voltages of various sizes of polished parallel wires at various spacings. This was given in my paper before the A.I.E.E. in June, 1911. For any conductor the voltage gradient at rupture, g_v, was found to be constant, independent of the spacing (except at very small spacings), but increased very rapidly as the radius of the conductor was decreased. Thus air *apparently* had a greater strength for small conductors than large ones. This was formerly pointed out by Professor Ryan. The experimental data curve between g_v and radius r was found to be regular and continuous. A number of equations could readily be written which would fit these data. It was desired, however, to establish or build up a rational equation. The old idea of air films at the surface of the conductors was abandoned, after tests with very light (aluminum)and very heavy (tungsten)

metals showed that the density of the metal of the conductor had no influence on g_v, which should be the case if the difference were caused by air films, as the air film should vary with the density of the conductor.

A rational law of visual corona was deduced from the data, reasoning as follows:

Energy of some form—be this the $\sum \frac{m v^2}{2}$ of the energy of the moving ions, or whatever form it may—is necessary to rupture insulation. This is borne out by experiment with transients, which show that finite time is necessary to rupture insulation, and that if this time be limited the voltage must be increased to accomplish the same results in the limited time. Heating results at rupture, etc. These facts imply definite finite energy. The gradient or stress to rupture air in bulk in a uniform field, g_0, should be constant for a given air density or molecular spacing. In a non-uniform field, as that around a wire, the breakdown strength of air, g_0, is first reached at the conductor surface; at a small distance from the conductor surface the stress is still below the rupturing gradient. Hence, in order to store the necessary finite rupturing energy the gradient at the conductor surface must be increased to g_v, so that at a finite distance away the gradient is g_0. This means that a finite thickness of the insulation must be under a stress of g_0 or over. The rupturing energy is in the zone between g_v and g_0. The thickness of the zone should be a function of the conductor radius. It was found that at $0.301\ \sqrt{r}$ cm. from the conductor surface the gradient at rupture is always constant and 30 kv./cm. (at standard air density). The relation between g_v and r may now be directly expressed by the simple law

$$g_v = g_0\left(1 + \frac{0.301}{\sqrt{r}}\right) = 30\left(1 + \frac{0.301}{\sqrt{r}}\right)$$

For parallel planes or for air in bulk

$$r = \infty$$
$$g_v = g_0.$$

Thus the strength of air is constant and equal to 30 kv./cm., but in non-uniform fields is apparently stronger, as explained above. If the air is made less dense, that is, if the molecular spacing is changed, the strength of air in a uniform field should decrease directly with the air density.

$$g'_0 = \delta\, g_0$$

However, for non-uniform fields, the energy distance should also change thus

$$0.301\, r\phi\ (\delta)$$

I found this to be borne out by experiment and the complete equation containing air density correction to take the simple rational form

$$g_v = g_0 \delta \left(1 + \frac{0.301}{\sqrt{\delta r}}\right)$$

If the energy distance is limited to less than $0.301 \sqrt{r}$ the apparent gradient should increase. This also is borne out by experiment, as shown in later papers.* The visual tests on various forms of electrodes—as spheres, wires, planes, etc.—as well as loss measurements, all point to an energy storage distance and a constant strength of air of 30 kv./cm.

At *continuous* high *frequency* where the rate of energy, or the power, is great, frequency *may enter* into the energy distance, thus

$$0.301 \frac{r}{\delta} \phi (f)$$

and spark-over take place at lower voltages. Where the time is limited, as in an impulse of steep wave front, a much higher voltage should be required to start arc-over. This is also borne out by experiment.

Thus far, I have said nothing in regard to the form of this rupturing energy. Such speculation was not necessary in order to develop a rational working equation. After a law is developed it is interesting and instructive to fit speculative theory to that law.

In the discussion of my paper, *The Law of Corona*, 1911, Dr. Steinmetz suggested how the theory of ionization by collision could be made to fit the law of corona which had just been brought out. This suggested application is the same as that followed by Mr. Davis in his mathematical work, and is found on pages 1968, 1969 of the A.I.E.E. TRANSACTIONS for 1911. The theory that initial ionization could not affect the starting voltage is brought out on page 1122 of the A.I.E.E. TRANSACTIONS for 1912. I have also suggested the same application of the electron theory in my papers of 1912 and 1913, and also in discussions. Briefly, the rupturing energy may be the $\sum \frac{m v^2}{2}$ of all the ions necessary to produce ionic saturation, and hence conduction or corona.

When low potential is applied between two conductors any free ions are set in motion. As the potential, and, therefore, the

*See *The Law of Corona and the Dielectric Strength of Air*-II, (Peek), TRANS. A. I. E. E., 1912, XXXI, I, page 1051; and *The Law of Corona*-III, TRANS. A. I. E. E., Vol. XXXII, 1913, p. 1767.

field intensity or gradient, is increased, the velocity of the ions increases. At a gradient of $g_0 = 30$ kv./cm. ($\delta = 1$) the velocity of the ions becomes sufficiently great over the mean free path to form other ions by collision. This gradient is constant and is called the dielectric strength of air. When ionic saturation is reached at any point the air becomes conducting and glows, or there is corona or spark.

Applying this to parallel wires—when a gradient, g_v, is reached at the wire surface any free ions are accelerated and produce other ions by collision with molecules, which are in turn accelerated. The ionic density is thus increased by successive collisions until at $0.301\sqrt{r}$ cm. from the wire surface, where $g_0 = 30$, ionic saturation is reached, or corona starts. The distance $0.301\sqrt{r}$ cm. is, of course, many times greater than the mean free path of the ion, and many collisions must take place in this distance. Thus, for the wire, corona cannot form when the gradient of g_0 is reached at the surface, as at any distance from the surface the gradient is less than g_0; a finite thickness of air must be under a stress equal to or greater than g_0. The gradient at the surface must therefore be increased to g_v so that the gradient a finite distance away from the surface ($0.301\sqrt{r}$ cm.) is g_0. That is to say, energy is necessary to start corona, as outlined above. g_0 the strength of air, should vary with δ; g_v, however, cannot vary directly with δ, because with the greater mean free path of the ion at lower air densities, a greater "accelerating" or energy distance is necessary. In the equation

$a = 0.301\sqrt{\frac{r}{\delta}}$; that is, a increases with decreasing δ.

When the conductors are placed so close together that the free accelerating or energy distance is interfered with, the gradient g_v must be increased in order that ionic saturation may be reached in this limited distance.

Initial ionization of the air cannot affect the starting voltage, since such ionization must necessarily be very small compared to the residual ionization after each cycle. When, however, the initial ionization is very small when voltage is first applied, an appreciable time is necessary before corona starts. The starting voltage, however, is not affected for continuously applied a-c. or d-c. voltage. For transients of short duration, or for single impulse, much higher voltage should be required to produce the same results in limited time—that is, higher impulse voltages should be required to cause corona or spark-over.

Mr. Davis has mathematically connected the theory of ionization by collision with the law of corona already established. His results seem to indicate in a very interesting way that the rupturing energy may be the $\sum \frac{m v^2}{2}$ of the energy of the colliding ions. Of course this does not definitely prove this particular applica-

tion of the ionization theory. It shows that by a proper valuation of the constants, his equation will coincide with the established experimental equation. A number of equations might apply in the same way. It is interesting to quote as follows from his paper:

"The fact that equations (**14**) and (**15**) plot into almost identical curves is evidence that the theoretical equations express law of corona as accurately as the empirical equations."

The ionization theory will be more fully established for practical application when we may reverse this statement, or when theory so reaches the stage that we may say, "it is remarkable that the practical results so well check the theoretical ones."

Mr. Davis is to be congratulated upon the important work which he has done in actually applying theory to obtain practical working results. The electron theory has not been so definitely applied before to obtain practical results, but only vaguely and in a speculative way, fitting the theory to suit the particular case. It is such important work that will bring forward and extend this theory.

Bergen Davis (by letter): The discussions of my paper on the "Theory of the Corona" have interested me, and I appreciate the criticisms and suggestions which the various gentlemen have made. It is perhaps not necessary to take time and space for a lengthy reply, but I will consider a few points that seem to need further explanation.

(1) Professor Whitehead inquires why a constant density n of ions per unit area is assumed as a criterion for the appearance of the discharge. This is a natural assumption. The ionization progresses with the voltage according to a high exponential law. The rate of increase with the applied voltage is definite and can be experimentally reproduced at will. This refers to experiments with steady potentials applied to plate electrodes. The phenomenon is progressive until it becomes visible, and the ionization at *first* visibility is undoubtedly constant, at least for the same observer. This rapid rise of the ionization with the voltage has been found by all experimenters, and I would refer the reader to the numerous papers on this subject published during the last decade by Professor Townsend and his fellow workers. Professor Whitehead should have detected this partial ionization had his conditions been steady enough, and his detecting instruments of sufficient sensibility.

The origin of the constant $x_0 = 26{,}600$ volts per cm. is explained in the original paper. It was necessary to find an integrable equation that would agree with the theoretical expression (**7**) for the relation between α, p and x. This integral equation is

$$\frac{\alpha}{p} = A + B\left(\frac{x}{p} - 350\right)^2$$

The number 350 is a constant, and on eliminating p from the

parenthesis, when p is expressed in centimeters of mercury, one obtains $76 \times 350 = 26{,}600$ for the value of x_0 at normal pressure.

The physical meaning of the constant x_0 is that ionization by impact will occur at all gradients greater than 26,600 volts per cm. and that one may neglect all ionization at gradients below that value. As a matter of fact, the kinetic theory of gases shows that some ionization by impact may occur at any gradient, however small.

Professor Whitehead also questions the experimental basis of the theoretical equation (**7**). Since the publication of the paper on the corona, I have compared equation (**7**) with all the experimental results obtainable for the relations between α, p and x. If one takes $v = 11.5$ volts, and the mean free path of an electron to be eight times that of a molecule, then equation (**7**) agrees with the experimental results with an accuracy of five per cent or better. The validity of this equation is thus supported by all of the experimental work on ionization by impact.

(2) The points made by Professor Bennett. It is not assumed that ionization will first be evident at that half-cycle in which the electrons move towards the wire. Ionization by impact occurs when the electrons move outward as well as inward, but the *first* appearance of the visible corona will occur when the wire is on the positive phase. After the discharge is established, the ionization is very copious, and it probably occurs on both phases. That the discharge will occur when the wire is on the positive phase, is shown by the experiments of Prof. Townsend, (*Phil. Mag.*, April, 1914) who finds that for all pressures greater than 5 to 8 cm. of mercury, the discharge occurs at a less gradient for wire positive than when it is negative. The contrary is the case for smaller pressures. This theory is applied only at pressures greater than 5 cm. mercury. Professor Bennett's own experiments were made at 1 cm. pressure. He finds in this case that the discharge first occurs when the wire is negative. This also was observed by Professor Townsend. No matter whether the discharge occurs when the wire is positive or negative, the greater part of the ionization by impact is due to the negative ions.

Professor Bennett also has difficulty with the constancy of the left member of equation (**6**). The n_0 ions crossing Q inward are concentrated by the curvature. The geometry of the figure will show that the density of ionization will increase as the n_0 ions move inward without ionization by impact. The numbers n and n_0 refer always to the number crossing unit area. Now if the total number of ions outside of Q is constant, then it is evident that the number n_0 crossing the surface Q will be less as b is larger. The surface of a cylinder is directly proportional to its radius.

The concentration due to curvature will be as b to a, and the value of n_0 will be inversely as b for any given case. That is, one is justified in assuming $\left(\frac{n}{n_0}\frac{b}{a}\right)$ to be approximately constant.

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ELECTRICITY THE FUTURE POWER FOR STEERING VESSELS

BY H. L. HIBBARD

ABSTRACT OF PAPER

Electrical development in the marine field has been confined in a large measure to the navy, and the best experience with electric steering gears has been obtained from navy installations.

Up to the present time steam has been the universal power for operating steering gears, but certain disadvantages are inherent in this system which can be overcome by the electric drive, and additional advantages obtained. The history of electric gears shows that many different schemes have been tried and proved failures owing to faulty designs and imperfectly developed apparatus. At present several different systems are in successful operation.

To obtain full benefit of the advantages possible from an electric drive, much depends on the selection of apparatus with characteristics best suited to the work. The problem of electric drive is largely one of control. The calculations for rudder and motor horse powers must be carefully made, with the proper assumptions for the conditions presented.

Several installations in the navy have shown excellent results; in the case of the battleship *Texas* the data obtained show preliminary calculations were quite accurate. Results obtained seem to justify the prediction that electric steering gears will be used quite generally in the future.

THE MARINE field has probably been one of the most backward in the adoption and development of electrical apparatus owing, in part, to natural causes, such as high first cost of electrical over steam machinery, the long familiarity aboard ship with steam machinery, and the somewhat higher order of care and inspection required for electrical apparatus; but in the main we believe it has been due to the traditional conservatism of the seafaring man and his reluctance to try something new when that which has been used before seemed to answer the purpose, owing in a large measure, doubtless, to his belief that this policy insured the greatest protection to the lives and property under his care. The most conspicuous exception to this, however, has been the American navy, which is not only a larger user of electrical machinery than the merchant marine, but also leads the navies of the world in this respect.

During the last few years, however, considerable attention has been given to the development of electricity on board ship, and to many of the auxiliaries we have seen its application, as well as to the electric propulsion of ships, which is now also being given careful consideration. One of the auxiliaries of the greatest importance to the operation of the ship and which also involves some of the most interesting engineering problems, to which electric power and control is now being applied, is the electric steering gear. In line with our previous statement, however, the greatest use of electricity for this purpose has been in the navy, and, therefore, our future statements will refer in a large measure to naval installations of electric steering gears.

The Steam Steering Gear

Large steamers of the present day are fitted with either the ordinary form of rudder or with a balanced rudder, battleships being almost invariably fitted with the balanced type in order that they may maneuver more quickly. Fig. 1 illustrates the general arrangement of a steering gear controlled by a steam engine on a warship, operating a partially balanced rudder.

Practically all steamers except those of the smallest size at the present time make use of steam power for moving the rudder, and in addition to this power drive, most equipments include provision for steering by hand either through handwheels, geared to the steering gear, or by block and tackle to the tiller. The possibility of accident to the prime mover and the importance of avoiding a complete breakdown renders the addition of the manual drive necessary, although the rate of turning with the hand gear is, of course, much slower than with power.

The successful introduction of steam power for operating the rudder was made about 1866, by McFarlan Grey. A steam gear designed by him was placed on the *Great Eastern* and the ease with which steering could be done under the new power as contrasted with the old hand method, led to its rapid adoption on all classes of steamers. Improvements have, of course, been made in details, better engines being now made than formerly and better control of them obtained, but, nevertheless, the present steam equipment does not vary greatly from the first one installed.

The control of the valve of the steam engine from the bridge has been accomplished in various ways, in some cases by direct shafting and gears from the steering wheel, in others by wire

rope transmissions called tiller ropes, and in other installations, particularly of large capacity, by hydraulic telemotors. In practically all cases, however, the control has been by what has been known as the follow-up system, in which the arrangement of valve gear is such that the steam is cut off and the rudder

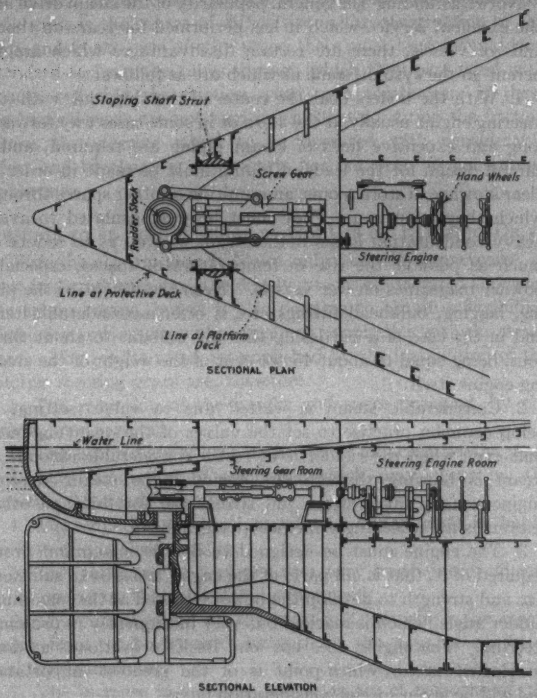

FIG. 1—STEERING ARRANGEMENT OF A WARSHIP OPERATING A PARTIALLY BALANCED RUDDER

stopped at the angle corresponding to the position at which the helmsman has set his steering wheel. With this arrangement the helmsman turns his wheel to the angle desired as shown by the indicator on the steering stand, and without further operation of the wheel the rudder moves to this point and is automatically

stopped. This system of control, we believe, has been used in practically all classes of vessels, with the possible exception of some large river steamers, and has been so generally used for many years as to be, in the mind of the mariner, an integral part of a steering mechanism.

Notwithstanding the general popularity of the steam drive and the excellent service which it has performed for years on thousands of vessels, there are certain disadvantages which are inherent in the system, some of which are as follows:

1. With the boilers near the center of the ship and with the steering engine usually at the stern or in some cases way forward, long and expensive lines of steam piping are required, and a careful design for the leads of piping must be made in order to clear stowage in store rooms, ammunition or other spaces through which they must run. They must be well insulated to avoid heavy condensation losses in the steam, as well as to reduce as much as possible the rise in temperature of spaces, especially powder magazines on war vessels. Even the weight of the piping, lagging, bulkhead fittings, etc., is often a considerable item, and in the case of a battleship this will amount to about three tons, being equal to about 45 per cent of the weight of the steering engine itself.

2. Considerable steam is wasted due to valve setting, it being common practise to set the valves of the steam engine so that even when the rudder is at rest a considerable amount of steam is blowing through the engine. The steam steering engine usually takes steam full stroke and for this and other reasons is an exceedingly inefficient mechanism.

3. The engine must be designed to do the maximum work required of it, that is, all parts of the engine must be of sufficient size and strength to develop the power required at the maximum rudder angle, which is reached but very infrequently in ordinary steering. The engine does not lend itself to overloads as does an electric motor, which point is of the greatest importance and will be given special consideration later.

4. The steam engine is provided with reciprocating parts which are subject to severe stresses when the engine speeds up due to sudden decrease of load on the rudder as it is moved back to a central position. These reciprocating parts do not produce a uniform torque, as in the case of a rotating armature, and they furthermore are the source of considerable vibration in the operation of the gear. When in harbors the steam engine

requires turning over at rather frequent intervals to prevent piston, cylinders, etc., from becoming rusty.

5. The mechanical connections from the bridge to the engine valve are a considerable source of trouble, and wire rope leads frequently wear out. The necessity of running these mechanical connections through compartments and watertight bulkheads is the source of difficulties in the construction of the ship, and in the case of wire ropes, there must be continual care exercised to keep the tubes through which they pass filled with grease, reducing the friction wear to a minimum. If these mechanical parts are not kept in excellent condition the friction causes the steering wheel to be operated with considerable effort and breakage of these parts has not been an uncommon occurrence.

Results to be Accomplished by the Use of Electric Drive

With the electric gear it is not only possible to overcome, at least in a great measure, the disadvantages enumerated above for the steam engine, but it is also possible to obtain a flexibility, simplicity and accuracy of control not permissible with the steam gear. The results to be accomplished by the installation of the electric steering gears are, therefore:

1. The reduction of the weight and space occupied by the driving mechanism;
2. The suppression of heat in the spaces adjacent to the gear;
3. The elimination of accidents which may occur in the bursting of steam pipes;
4. The reduction of vibration and noise and increase in habitability, due to these factors;
5. The obtaining of a mechanism very much more efficient in its operation than the steam equipments;
6. The simplification of the means of controlling the mechanism from the bridge, with increase in the ease of operation for the helmsman;
7. The increase in rapidity and accuracy of response of the rudder to the movements of the controlling mechanism.

History of Electric Gears

The subject of electric steering gears has been given some attention by engineers for the past 15 or 20 years, but within recent years only has the matter been given sufficient attention or the electrical apparatus developed to such a point as to per-

mit of successful results being attained. Several electric steering gears of different types have been tried in foreign navies, but it is not known whether any of them have proved completely satisfactory. In a great many cases after being thoroughly tried out they have been stripped and the steam gear again used, some doubtless being defective in design and some in the perfection of details, but others failed due in a large measure to flaws in the controlling apparatus.

At the present time motors and controlling appliances have been developed to such a point as to permit readily of the solution of the problems involved and also to render their performance reliable and trustworthy. The main feature in the electric steering gear has, however, become one of control, and too much emphasis cannot be laid on this point. This problem of control has been attacked by several radically different schemes, the principal ones being outlined below.

Direct current is used universally on board ship, with pressures varying from 80 to 220 volts; the present standard in the American navy is 125 volts, with many of the older ships provided with 80-volt equipments, while in the German navy the voltage is 220, and the same is now being considered by the U. S. naval authorities and has recently been adopted on one of the latest battleships as a trial experiment. It is not necessary, furthermore, to give consideration to the use of alternating-current motors for operation of steering gears, this current not being employed to any extent on shipboard, and such motors would not give the varying torque and speed characteristics which are here especially desirable.

One of the earliest electric steering gear systems considered in this country was known as the Van Duzer-Mason system and was patented about 1893 and is described in the Proceedings of the U. S. Naval Institute of that year. This system contemplated the use of a motor direct-connected to the rudder mechanism and its operation controlled by a simple form of controlling device operated on the follow-up system, but so arranged as to follow up at only a limited number of definite angles of rudder travel, and produced, therefore, a very coarse control. It is not known on what vessels this scheme may have ever been tried.

Several systems involving the use of magnetic clutches between the motor and rudder gear and of differentially controlled mechanisms have been tried, but for various reasons have not proved successful.

One of the first successful electric steering gears is that designed by Mr. Mathias Pfatischer and known as the Platischer system. This gear was placed on eight of the Imperial Russian naval vessels, a number of which were destroyed or captured by the Japanese during the recent Russo-Japanese war. It was also installed on two large liners built in this country for the Pacific trade and has been in constant use since 1902 on the liner *Finland*. One equipment has also been installed by the U. S. Navy on the cruiser *Montgomery* and we understand its operation has been generally quite satisfactory.

This system generally employs a shunt motor for operating the rudder, which is controlled with the varying voltage system by a motor-generator set especially supplied for the purpose. The field of the generator or generator exciter is controlled from the steering stand at the bridge on the Wheatstone bridge principle, the bridge being formed by one rheostat located at and operated by the steering stand and the other located at and operated from the rudder crosshead. The unbalancing of the bridge rheostat by the movement of the wheel gives current to the generator field and therefore, voltage and current to the rudder motor. The balancing of the bridge again by the movement of the rudder crosshead cuts off current from the generator field and the motor is stopped, constituting an electric follow-up control.

Objections which may be offered to this system are the size, weight and cost of the motor-generator set, which, furthermore, is always in rotation even though the rudder is at rest, and the no-load current of this set is an appreciable amount, being as much as 25 to 30 amperes on sets as small as 25 h.p. With this type of follow-up also the available power of the rudder motor is proportional to the unbalancing of the Wheatstone bridge and approaches zero as the balanced position is reached, which is the point frequently where the maximum torque is desirable, and the result must be the installation of a motor larger than would otherwise be necessary.

Several years ago the Navy Department became interested in the question of steering its ships by electricity owing to the possibilities presented of effecting the economies outlined above for the electric gear. In about 1902 the Department devised a steering gear operated on the follow-up system, and purchased apparatus of different manufacturers to effect an installation on one of the small monitors which had been recently constructed.

The results obtained from this equipment were not satisfactory. The question, however, remained under discussion for a number of years until about 1909, when a contract was placed for supplying an electric steering gear for the cruiser *Des Moines* as an auxiliary to the steam engine outfit. For this purpose the use of an electric motor taking its power directly from the dynamo mains and operated by a powerful automatic controller, thus eliminating the necessity of a motor-generator outfit, was advocated. The contract specified that no payments should be made unless the gear proved itself satisfactory in service and in the event of its failure it was to be removed by the contractor at his expense. The contract further required the control of the motor to be similar to that of the steam engine, *i.e.*, the follow-up system must be employed, and to accomplish this a small follow-up drum controller was provided in the steering engine room and operated differentially by the ship's tiller rope from the wheel on the bridge and the motor driving shaft.

The preliminary trials of this arrangement of gear were quite successful, although the writer found upon going aboard the vessel before the trials, that the officers and crew were prejudiced against the electric gear and considered it an unwelcome visitor on their vessel. After the successful preliminary trials of the follow-up gear the prejudice was overcome and it was then suggested that a non-follow-up type of control would be much simpler and easier to operate, but the reply was made that officers and men had steered with the follow-up system for years and it was foolhardy to think of adopting any other type. After considerable persuasion, however, permission was granted to install on the bridge a small reversing switch controller operating the main controller through four small wires and thus entirely cutting out of the operation the steering wheel and the tiller rope connections. After about a month's trial of this system of control the first report to the Department states in effect that the quartermaster and helmsmen learned to steer by this new method in about five minutes and now much preferred it to the old wheel control. Steering by the non-follow-up system on this vessel, therefore, became the prevailing fashion.

Although the reports from the *Des Moines* were of a satisfactory nature, the Navy Department was still naturally doubtful about the use of electric steering equipments, especially as regards the elimination of the follow-up principle. It was decided, therefore, to install such a gear as this on the scout cruiser

Chester, to be operated only by the non-follow-up system, and remove the steam gear entirely in order that confirming opinions might be obtained of abandoning the time-honored follow-up control and of steering naval vessels by electricity. Contract was, therefore, placed for the installation of a similar equipment of 75 h.p. on the *Chester* as against the *Des Moines'* 40 h.p. equipment, and this installation was completed the early part of 1912, about two and one-half years after the first installation had been made on the *Des Moines*. The motor with disk brake for the *Chester's* equipment is shown in Fig. 2.

Since this time installations of the same type of gear of 150 h.p. capacity have been made on the battleships *New York* and *Texas*. A further description of these equipments and of many of the results obtained will be given later.

Other installations of electric steering gears have recently been effected by another manufacturer on the Argentine battleships *Rivadavia* and *Moreno*, which are just reaching completion at shipyards in this country. These equipments consist of a 150-h.p. motor, 400 to 600 rev. per min., operated with combined rheostatic and field control. The motor operates the rudder at a lower rate of speed than the steering gear engine, to which it is considered an auxiliary, the requirements being hard-over to hard-over in 40 sec. The motor in question is shown in Fig. 3.

The controller consists of a contactor panel provided with four reversing contactors, a dynamic brake contactor, five accelerating contactors and other small contactors for controlling the field strength and the electromechanical brake.

The master controller is driven by a differential gear in order to provide the follow-up feature. Transmission from the steering wheel to the steering room is accomplished by hydraulic telemotor or wire ropes that are used for the steam engine control. The steam valve may be disengaged by a clutch, and the part of the differential gear, which operates the controller, connected in place of it, and the other part of the differential gear is connected to the steering gear itself. When the controller is turned to a certain point by the steering wheel, the motor begins to turn and will continue to turn until the action of the differential gear, driven by the steering gear itself, turns the controller to the "off" position and stops the motor.

The first position of the controller closes the proper reversing contactors and the current passes through the armature and all of the starting rheostat. The first accelerating contactor then

closes, and after the motor has speeded up sufficiently the next contactor automatically closes, allowing the remaining three to follow quickly after each other, bringing the motor up to the speed corresponding to the full field strength. If the controller is turned further than this, one of the field contactors is opened and the field weakened; a little further motion of the controller opens the second field contactor, still further increasing the speed.

A limit switch, carried on the same shaft as the master controller cylinder, automatically strengthens the field of the motor when the rudder has been turned to a certain definite angle from the mid position, and at a greater angle the field is strengthened still more, bringing it up to its full field strength. This provides an increased torque per ampere when the rudder is a considerable angle from the mid-ship position.

As the rudder returns to the position for which the steering wheel is set, the controller is turned to the "off" position, and if the rudder should be inside of the limits of 10 deg. either side it will be running at full speed. Just before the "off" position is reached the field is strengthened by one contactor. This increase of field strength causes a current to flow from the motor armature into the line, exerting a dynamic braking effect and reducing the speed of the motor. A moment later the field is strengthened again with the same effect, so that at the instant the main contactors open and the motor is disconnected from the line, the speed has been considerably reduced. The dynamic brake is then applied by the action of the proper contactor and the electromechanical brake follows an instant later.

As is later shown, the use of a compound winding exerts a greater torque per ampere with heavy loads, but owing perhaps to the relatively high speed of the armature and the necessity of very accurate stopping with the follow-up control, it seems to have been considered advisable to produce a slowing down effect before the brakes were applied. For that reason a shunt field was used on these equipments, which can be strengthened just before disconnecting from the line. The motor is provided with a small amount of series field winding but it is essentially, in its characteristics, a shunt motor.

The limit switch, besides performing the function of strengthening the field at certain positions of the rudder, will also cut off the power at the end of its movement if it is not already cut off by the movement of the controller. An overload relay is provided, which re-inserts the starting resistance in the armature

FIG. 2 [HIBBARD]

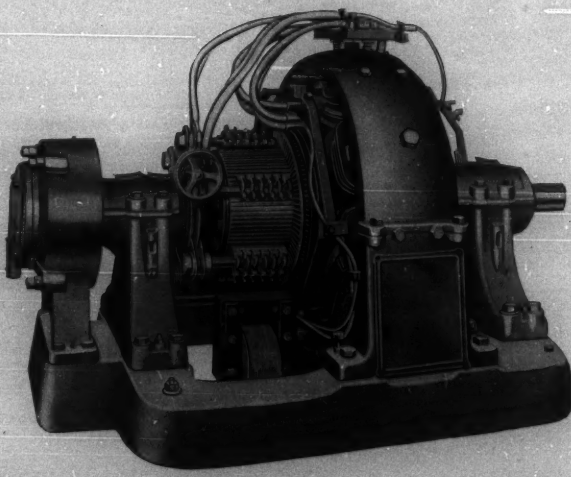

FIG. 3 [HIBBARD]

FIG 5 [HIBBARD]

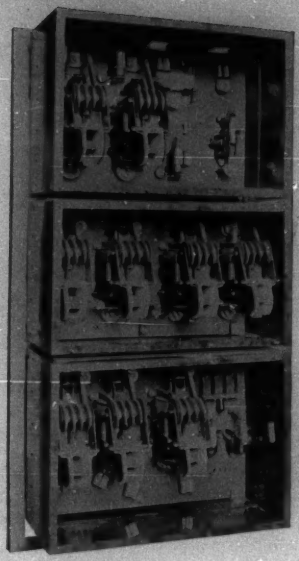

FIG. 6 [HIBBARD]

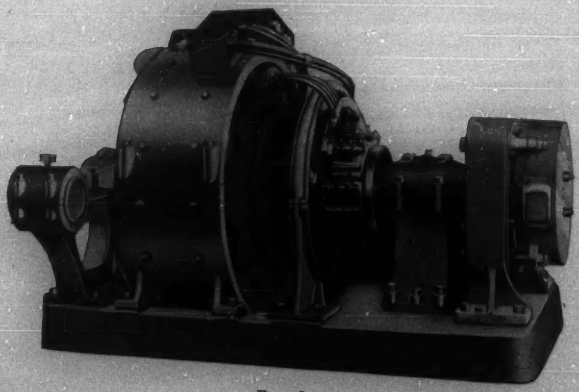

FIG. 8 [HIBBARD]

circuit in case of overload, instead of interrupting the circuit entirely.

We believe these equipments have not yet been tried out in service and we cannot, therefore, comment on results obtained.

The same company is also providing an electric steering gear for the American navy, which is to operate the rudder in the same time as required of the steam engine. The equipment consists of a rudder motor, motor-generator, switchboard, steering stands, selective switch and limit switch. The speed of the motor is controlled by varying the field strength of the generator according to the variable-voltage system and the system has no follow-up device. The motor is rated at 350 h.p. and when operating at rated voltage and full load, has a speed of 250 rev. per min.

The motor-generator is rated at 290 kw. output and runs at a speed of 1000 rev. per min. The motor has an accumulative compound winding and the generator a differential compound winding, so that the extreme overloads of voltage on the generator will be reduced both by reduction of speed and by the demagnetizing effect on the generator field; also the reduction of speed will deliver considerable energy for a few seconds to the generator circuit. The motor of the set is wound for 120 volts to agree with the ship's voltage, but the generator and the motor which moves the rudder are wound for 250 volts. The steering gear motor is compound-wound, taking series current from the armature of the motor driving the motor-generator, and the shunt field is strengthened by a relay at a definite overload on the motor.

There are four steering stands; three of them forward and one aft, anyone of which may be connected to the panel by means of a selective switch.

The controlling panel contains the necessary contactors for starting up the motor of the motor-generator set, as well as an ammeter and an overload relay, for the generator the necessary field switches and ammeter and voltmeter, also the motor field relay for strengthening the field of the steering gear motor and a step-back relay which inserts resistance into the field of the generator in case of excessive overload, performing the same purpose as the overload relay in the rheostatic system previously described.

The various steering stands have three speed positions in each direction; in the first, the field of the generator is excited to give a low voltage for slow speed; the next step strengthens the

field, and the next step fully excites the generator field, giving full speed of the motor.

The limit switch, which is operated by the steering gear, is provided to cut off power at an extreme movement in either direction without interfering with the return motion after the steering stand is reversed.

In connection with this system, the same criticism may be offered as regards size, weight and power required to operate the motor-generator, as was mentioned in case of the Pfatischer system.

Description of 150-h.p. System on Battleship *Texas*

It is not the purpose of this paper to draw close comparisons between the features and merits of the several electric systems of different manufacturers which have been proposed or installed and which are at present receiving the close attention of the Navy Department and others interested, but rather to point out the salient features of these different systems. Our future remarks apply largely to the system previously referred to, taking power directly from the dynamo mains, with which the writer is most familiar and from which also our data have been principally obtained. As an illustration of this system and of many of the points to be covered in the design of an electric steering gear we give a description of the apparatus and design of the installation on the battleships *Texas* and *New York*.

The electric installation on the *Texas* and *New York* (and with few minor differences those of the *Des Moines* and *Chester*, later transferred to the *Mississippi*, were exactly the same except as to reduction in horse power) includes the electric motor with disk brake installed in the steering motor compartment as illustrated in Fig. 4, the main automatic controller and resistance near the motor, and, in the compartment where the screw gear is located, a limit switch; master controllers or steering stands are furnished, one on the bridge, one in the conning tower, one in the central control station and one in the steering gear room. The steering stand is shown in Fig. 5, and contains within, a reversing switch for governing the main contactor controller in the motor room. The reversing switch is operated by the lever shown, and closes the circuit to the contactors of the automatic controller through several contact fingers. A latching device retains the lever in the center position; the pressure of the hand on top of the lever releases the latch, while a centering

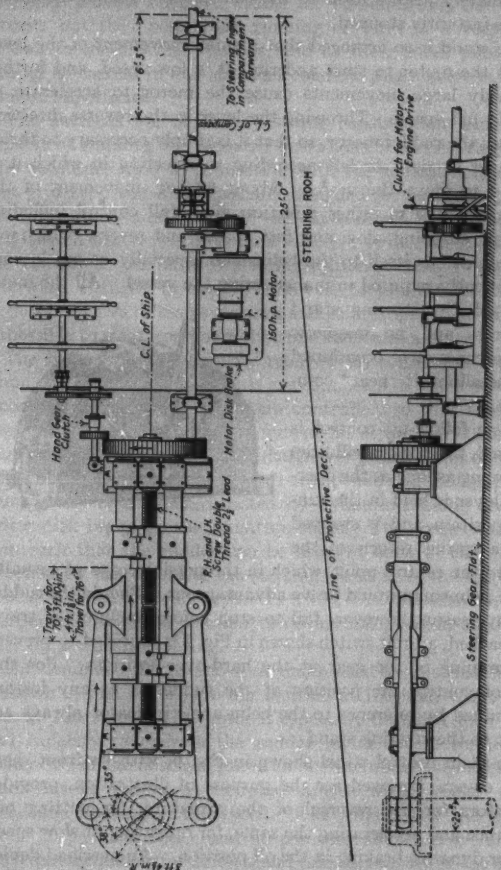
6'-3"
To Steering Engine in Compartment Opposite
C.L. of Ship
25'-0"
STEERING ROOM
150 h.p. Motor
Motor Disk Brake
Head Gear Clutch
R.H. and L.H. Screw Double Thread 2½" Lead
Line of Protective Deck
Clutch for Motor or Engine Drive
Steering Gear Flat
35°
35°
35 to 40 h.p.

FIG. 4

spring acts to return the lever to the "off" position, and should the hand be removed from the lever in a running position it will immediately restore itself to the central point, when the motor will be instantly stopped.

The stand is so arranged that a small movement of the lever causes the motor to start and run at a low speed, and further relatively large movements cause the motor to accelerate at once to full speed. Throwing the lever in the reverse direction reverses the rudder motor, so that it is simply necessary to throw the lever to right or left according to direction in which it is desired to move the vessel. About 60 deg. movement of the operating lever in either direction gives full control, including starting, stopping, slow and fast speeds and reverse, which feature commends itself to the helmsman especially, as quick work is frequently required in maneuvering the vessel. All the metal parts of the steering stand are brass and no magnetic interferences are occasioned by installing it near compasses.

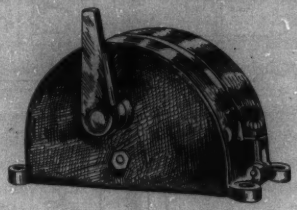

Fig. 7

As no follow-up control is involved, the rudder will keep on moving as long as the operating lever is held in the running position, and is stopped by the spring return of the lever to the central point, which in the possible case of casualty to the helmsman would prove advantageous. Should the rudder for any reason, however, fail to stop before the limits of travel are reached, a limit switch shown in Fig. 7 is provided to prevent the jamming of the gear at the hard-over positions. For this type of control the position of the rudder is at any instant determined by reference to the helm angle indicator always adjacent to the steering stand.

The main control panel shown in Fig. 6, with its front sheet metal covers removed for the purpose of illustration, provides contactors for the reversal of the armature, for cutting out resistance and accelerating the same, for operating at slow speed and for dynamic braking in the off position. An overload device is provided also, which in the event of jamming the gear or other extreme overloads automatically limits the current on the motor to a safe value, and by its use the necessity of circuit breakers

and fuses, whose blowing would be very dangerous to the operation of such a system, is obviated. The electrically-operated switches not only provide effective means for commutating the motor circuits but they permit the running of wires of a very small section to the steering stations, and as these small pilot wires can all be carried in one lead and conduit, this feature is of the utmost importance.

The switches are of a very strong construction and easily capable of standing the repeated operations of the steering gear. The resistance used in connection with the controller is of the cast grid type and also especially designed for heavy duty. In the lower right-hand corner of the cut is shown a small double-pole switch which functions as a selective switch for delegating the control to one of two steering stations. This switch was afterward changed in design, however, to provide for control from four or five different stations and so arranged as to make it impossible to steer from more than one station at a time.

The limit switch previously referred to, consists of a small, drum controller whose segments are connected in series with the secondary circuits from the main controller, so that when the dogs connected to the traveling nuts of the screw gear engage the lever of the limit switch at the hard-over position and open the same, the main contactor switches are opened and the equipment immediately shut down, assisted by dynamic braking and the motor disk brake on the armature shaft. The connections are then such that the rudder can be brought back in the reverse direction by movement of the steering stand lever in that direction, and when the rudder moves away from the extreme limit position the switch is restored to its normal position automatically by a centering spring.

The combined motor and disk brake used in this installation is shown in Fig. 8. The motor is rated at 150 h.p., 250 rev. per min. at 120 volts. The motor is especially designed with overload capacity to operate the rudder under severe conditions, taking care of the power required to operate under the infrequent conditions of rudder at extreme angles with vessel going ahead and backing at full speed. The windings of the motor, about 50 per cent series and 50 per cent shunt, give variable speed and torque characteristics and take advantage of the variation in load from center to hard-over positions, giving a quick response to the rudder, especially in the central angles, and heavy torques at the extreme angles, and permitting the installation of

an equipment smaller in rated horse power than would otherwise be required, especially as compared to a steam engine, which point has been previously brought out. The motor is capable of carrying 100 per cent overload for short periods of five minutes or more.

This installation was made as an auxiliary to the steam gear and the requirements for the operation of the rudder were 20 deg. right to 20 deg. left in 20 seconds, as against 35 deg. right to left in 20 seconds for the steam engine, and naturally resulting in a smaller equipment than if full duty had been required. In the case of a later battleship, the electric gear is required to operate the rudder at the same time as the steam engine and this system has, therefore, been provided, for that vessel, of 300 h.p. capacity, dividing the same between two motors of 150 h.p. each.

Calculation of Horse Power for the Above Installation

When a vessel is underway and the rudder is at some angle with reference to the keel line of the ship, the water impinging on the rudder surface undergoes a change in momentum, the result of which is dynamic pressure against the rudder and twisting moment about the rudder stock. The center of application of this pressure on the rudder, which varies with each angle, may be found by the use of some empirical formulas. An empirical formula is required, as the lines of action of the various streams of water are in different directions at various parts of the rudder, due to the shape of the vessel's stern, the influence of friction against the hull, the action of the propellers, etc. In navy work Joessel's formula is principally used, in which

d = distance of center of pressure from forward edge of rudder
b = breadth of rudder
a = angle made by plane of rudder with line of motion

$$\text{then } d = 0.195b + 0.305b \sin a$$

The twisting moment about the rudder stock is, of course, the product of the total resultant pressure on the rudder area, and the distance d of the point of application of the pressure from the center of the stock.

Let P = total pressure on the rudder in pounds
V = speed of ship in knots
A = area of rudder in square feet
b = horizontal length of rudder plane
d = distance of center of pressure from leading end of rudder

a = angle of rudder with fore and aft plane

$$\text{then } P = 4.6\, K\, A\, V^2 \times \frac{\sin a}{0.39 + 0.61 \sin a}$$

Usually 35 deg. is the maximum helm angle, in which case

$$P = 3.57\, K\, A\, V^2 \qquad d = 0.37\, b$$

For battleships and cruisers K varies from..... 0.60 to 0.75
" gunboats and small slow vessels of 900 tons and up, K varies from.....0.55 to 0.65
" torpedo boats and destroyers K varies from.. 0.45 to 0.55

A small coefficient is associated with small vessels, relatively large rudder areas, high speed of the ship and low speed of helm; and a large coefficient is associated with large vessels, relatively small rudder areas, low speed of ship and high speed of helm.

Theoretically the pressure P will increase to an angle of 45 deg. but ordinarily 35 to 40 deg. is the maximum angle of rudder throw. The equipment must be of sufficient size so that when the rudder is near the hard-over position sufficient power is available for its operation, and this point is, therefore, of chief importance in design and rating of the motor. In the case of the steam engine it is considered that with one-half of the full boiler pressure on one cylinder it should have sufficient torque to move the rudder, the crank of the other cylinder being supposedly temporarily on the dead center.

The pressure P and the center distances d are determined from the above formulas for a number of rudder angles, ranging from center to hard-over position, and the twisting moment in foot-pounds torque for each angle obtained as the product of the two.

After obtaining the twisting moment on the rudder the turning moment at the prime mover is to be ascertained by taking into account the gearing and friction losses and the angularity of the connecting links in the case of a screw gear.

The calculated, or actual curves if available, of the compound motor which it is desired to use, are then set down, as illustrated in Fig. 9, in the form of percentage speed and load curves, it here being of the greatest importance to select the characteristics of the motor in such a way as to take the greatest advantage of increasing torque with increase in rudder load.

A curve sheet is then prepared of rudder torque, horse power and speed, as shown in Fig. 10. The rudder torques are figured for the various angles from the formulas, and the percentage rudder torque curve then calculated, allowance being made, however, in the rudder torques for friction of the rudder stock, which in this case has been assumed to be 25 per cent of the normal calculated rudder torque. On curve sheet Fig. 9 it will be noted that the motor characteristics have been chosen to give 280 per cent torque at 100 per cent overload on the motor, and as we desire the motor to have about 100 per cent overload

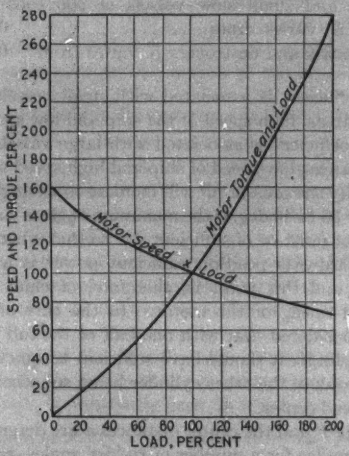

FIG. 9—CALCULATED CURVES FOR ELECTRIC STEERING GEAR FOR U. S. S. *Texas*

at 35 deg., the total rudder torque at 35 deg. therefore represents 280 per cent torque. The torque at 35 deg. representing 280 per cent, the 100 per cent point of the percentage curve is readily found, as is also the corresponding normal point of calculated rudder torque from which it is obtained by adding the 25 per cent for friction. We have thus obtained the percentage torque curve and the 100 per cent point, where the motor, of the characteristics which we have chosen, reaches 100 per cent torque full load and normal speed and which point, it will be noted, comes at 16 deg. of rudder travel.

From the motor curves in Fig. 9 the percentage motor speed curve can now be easily figured in per cent of motor speeds for the rudder torque or load at the various angles. Having obtained the percentage-torque and percentage-speed curves, the percentage-motor-horse power curve is readily obtained as the product of the two. As it is then necessary to figure in this case the motor speed over the required range of 20 deg. each side of the center, a number of points are taken on the percentage motor speed

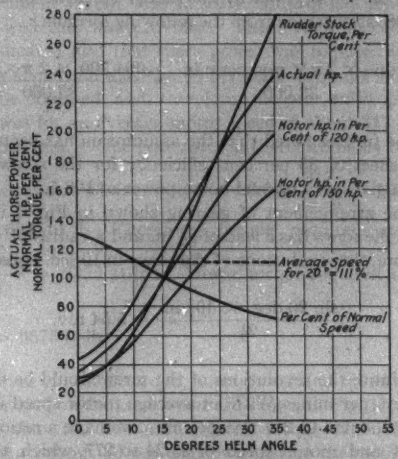

FIG. 10—U. S. S. *Texas*, CALCULATED RUDDER TORQUE AND POWER CURVES

Maximum rudder torque and power calculated from 1,860,000 ft-lb. at 35 deg. rudder angle.
Friction of rudder stock 25 per cent of normal rudder torque.
Efficiency of gearing 35 per cent.
Compound motor rated 150 h.p. used. (Curves based on 120-h.p. motor).

curves from 0 to 20 deg. and the average obtained, giving us in this case an average motor speed of 111 per cent over a range of 20 deg. of the rudder travel.

The requirement that the rudder must be operated 20 deg. right to 20 deg. left in 20 seconds gives a rudder speed of 0.333 rev. per min., which is the constant average speed of the rudder throughout this range. Dividing this quantity by 111 per cent, a rudder speed of 0.3 rev. per min. at full speed of motor is ob-

tained and which, it will be noted, obtains at the 16 deg. angle. With this figure as a basis the rudder speed for the other angles of throw are obtained from the per cent speed curve. From the figures of rudder speed and the corresponding torque in foot-pounds at this same angle, the horse power at the rudder stock for each angle is obtained.

From the curve sheet it will be noted that the rudder torque at 35 deg. is 1,860,000 ft-lb., and at 16 deg., 664,300 ft-lb. Therefore, the horse power at the rudder stock at 16 deg. of the rudder is 38, as obtained from the following formula.:

$$\text{h.p.} = \frac{\text{torque} \times 2\pi \times \text{rev. per min.}}{33{,}000} = \frac{664{,}300 \times 2\pi \times 0.3}{33{,}000} = 38$$

It will be further noted that the assumption has been made in the curve sheet of 35 per cent efficiency for the screw gearing, which then gives us a normal horse power of 108.5.

From the arrangement of gearing shown in Fig. 4 it will be noted that the screw has a lead of $2\frac{1}{2}$ in. and a radius of yoke $40\frac{1}{2}$ in., therefore, the revolutions of the screw in 10 sec. equal

$$\frac{\sin 20 \text{ deg.} \times 40\frac{1}{2} \text{ in.}}{2\frac{1}{2}} = 5.54 \text{ rev.}$$

For one minute the revolutions of the screw would be 6×5.54, or 33.24 rev. per min. With an average motor speed of 250×111 per cent, equal to 277 rev. per min., we have a ratio between screw shaft and motor speed of 33.24 to 277, which, therefore, gives us an indication of the spur gear ratios which are to be installed between the screw and the motor.

The ratio then determined should now be checked against the torque required to move the rudder at 35 deg., considering the effect of the angularity of the screw gear links, to see if the motor has sufficient torque available for the work under these conditions.

$$\text{The torque ratio at 35 deg.} = \frac{40.5 \times \cos 35 \times 2\pi}{2.5} = 83.5$$

$$\text{Therefore, } 83.5 \times \frac{277}{33.24} = 694 \text{ to 1, total ratio at 35 deg.}$$

$$\text{Torque required at 35 deg.} = \frac{1{,}860{,}000}{694} = 2680 \text{ ft-lb}$$

Motor torque required at 35 per cent efficiency of gearing

$$\frac{2680}{0.35} = 7675 \text{ ft-lb.}$$

It will be noted the curves were originally based on a 120-h.p. motor, the normal load coming at 16 deg. and 100 per cent overload at 35 per cent, and the calculations above would seem to indicate that this motor would have been sufficient for the service. The government did not wish to see a motor of less than 150 h.p. installed, and this was provided. Later tests on other installations indicated also that more power was required in backing than going ahead and that the 35 per cent efficiency would probably not be obtained, and, therefore, the gear ratio as actually installed was for an average motor speed of about 317 instead of 277 rev. per min. Our gear ratio is therefore 33.24 to 317 and the torque ratio at 35 deg. would be $83.5 \times \frac{317}{33.24} = 796$ to 1, instead of 694 to 1. Therefore, torque required at 35 deg. $= \frac{1{,}860{,}000}{796} = 2335$ ft-lb. Motor torque required at 35 deg. $= \frac{2335}{0.35} = 6675$ ft-lb.

The curves of actual torque, horse power and speed of the 150-h.p. motor used on the equipment are shown in Fig. 11, and it will be noted that the above calculated torque of 6675 ft-lb. is equivalent to about 80 per cent overload on the motors, coming at a higher point than indicated on the horse power curve in Fig. 10, owing largely to the fact that the motor has slightly different characteristics from those assumed in Fig. 9.

Some Results Obtained

The results obtained from trial tests and service operation of the installations of this gear have been very satisfactory, and the official trials of some of these will be reviewed briefly.

As soon as the *Chester* installation was completed the early part of 1912 and the vessel put to sea, she was ordered to meet the *Carpathia* at the time of the *Titanic* disaster, and was engaged in this mission about a week during the initial trial of the gear, upon which she had to rely entirely for power steering and the only means of steering from the bridge. Shortly after the

completion of this duty she was ordered to the ice fields to report the presence of icebergs and was engaged in this work for several weeks. She was then in continuous service until placed in reserve about September of that year, and although the performance of her electric gear had been most satisfactory, the gear was then removed and installed on the battleship *Mississippi* and the *Chester's* steam gear replaced, owing to the fact that this vessel

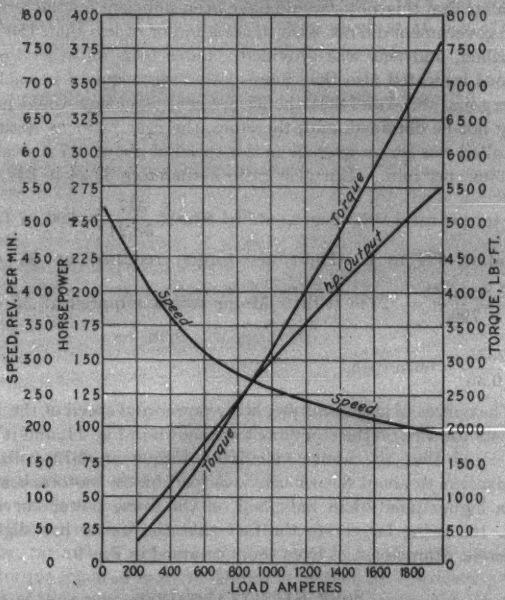

FIG. 11—ACTUAL CURVES—150-H.P. 120-VOLT, 250-REV. PER MIN., COMPOUND-WOUND, STEERING-GEAR MOTOR, U. S. S. *Texas*.

was supplied with a limited dynamo capacity. As the Department decided it inadvisable to increase her dynamo capacity, this procedure was necessary.

As a result of these trials and experiments on the *Chester* the commanding officer of that vessel reported that he considered this steering gear device unusually satisfactory, and an improvement on the steam gear with telemotor control:

1. In accuracy of steering
2. In the ease of operation for the helmsman
3. In the vibration of the ship
4. In the heat and moisture of the after part of the ship.

He further stated that he was surprised to see how accurately and with what little motion of the ship it was possible to steer, and that the response of the rudder to the movement of the master switch was rapid, and that the helmsmen were able to keep the ship on her course with small angles of helm and very little effort. The executive officer of the same vessel in his comments stated that "From my observation of this steering gear I should say that the non-follow-up master-switch type of control is entirely practical and suitable, and the quartermasters and helmsmen all prefer the master-switch control to the old wheel control."

It is, of course, very natural for an old seaman to throw his wheel to port upon receiving an order to starboard his helm, but the above comments show that these seamen are able readily to learn the new method, and one of its most natural advantages is that to steer the ship to starboard or port, or right and left, as it is now termed by the Navy Department, the helmsman has simply to throw the operating lever in the direction desired, which is the most logical operation to perform and in contradistinction to the old system, which was the reverse of a natural tendency.

An analysis of the conditions and of the electrical apparatus provided, indicates quite clearly that the above results would naturally follow, especially as compared with the steam gear equipment. The operation of the master switch is naturally easy for the helmsman, and there being no lost motion or mechanical parts between the bridge and steering room, the appreciable time lag with the old steam gear is eliminated. This absence of lost motion and the natural rapidity with which a motor, particularly of this design, can be accelerated, gives practically instantaneous response to the motion of the operating lever. Over the center angles of travel also, where the major part of the steering is done and load is light, the response would naturally be very prompt and the speed higher than at the extreme angles.

It was further noted by the officers of both the *Des Moines* and *Chester* that there was an appreciable saving in steam consumption over the steam engine, and it should be noted in this connection that with the steam engine some steam is always passing through the engine valves even with the rudder standing

still, causing a waste of steam in addition to that consumed in the operation of the engine, which is naturally of low efficiency. In the case of the electric gear, in addition to its natural high efficiency, the motor is started and stopped each time the rudder is started and stopped and the current is entirely cut off when the rudder is at rest.

A small amount of heat is generated in the rheostat control of the motor but it is quite insignificant as compared with that of the steam engine and not sufficient to cause any inconvenience in the compartments adjacent. On the *Des Moines* the officers' mess room is located not more than 20 ft. (6 m.) from the steering engine room, yet they reported no inconvenience whatever from the heat experienced, even in the tropics.

One of the officers on the *Des Moines*, after a cruise through the tropics, reported that with the temperature at 82 deg. fahr. on the bridge, that of the steering and engine room was 98 deg. fahr., and the comment was further made, which forms a very convincing argument in this connection, that a quartermaster on the vessel had complained that "in the old days when we had steam on here we could dry clothes in the steering engine room in twenty minutes, but now that place is no good for drying clothes."

We are also pleased to include the final comments of this officer, Ensign W. A. Edwards, in the article prepared by him for the Naval Institute Proceedings after he had served some time on both the *Des Moines* and *Chester*.

"From the intimate relations which I have had with this method of steering, from the most excellent results which I have seen produced and from the numerous advantages which it seems to possess over any other method in use today, I cannot help but feel that the electric steering gear is up-to-date and furthermore, that it has come to stay."

He further says: "In summation of the above remarks I would say that at the time of the present writing, Nov. 15, 1912, the *Des Moines* has covered 3600 miles (5793 km.) in continuous service, most of which was done in the tropics, during which time the electric steering gear was used constantly without a single breakdown of any kind."

With reference to Ensign Edwards's above statement, the writer wishes to explain, however, that thereafter a few minor difficulties were experienced with the *Des Moines* gear due to breakage of certain parts, owing to the largely experimental nature of her equipment. The installation was recently overhauled at the

navy yard, the minor defects in this first installation remedied, and the *Des Moines* is again in the tropics with the electric gear as the only means of steering.

The battleship *Texas*, the special description of whose gear is given above, was during the latter part of October on her official trial trip, lasting in all about 12 days. As she left the shipyard the steam steering gear was in use and the electric gear not thrown in until about a day later when the vessel was some distance up the coast. Although this electric gear was an entirely new equipment to all those on board and in charge of its operation, it at once made friends and the steam gear from that time until the vessel returned to the shipyard, about ten days later, was not put into operation except for two or three hours to actually try out its operation, and the electric gear was immediately thrown in again after this short steam trial. The power required in the operation of the electric gear, both in tests going full speed ahead and full speed astern, is shown on the curve sheet in Fig. 12. In going astern the engine revolutions were about 80 per cent of the revolutions at full speed ahead.

The curves taken from the recording ammeter used during the trials, while giving a good relative indication of the performance of the gear at various points in the rudder travel and under various conditions, cannot be taken as an accurate representation of actual motor values, the meter in question having met with an accident during the preliminary trials which required repairs at sea without an opportunity of careful re-calibration, and as compared to portable direct-reading test meters which were also used and the dynamo room meters the recording meter, shows at times an excess of current values of 25 to 35 per cent. In the case of the peak starting currents, however, the inertia of the switchboard and test meter needles would probably prevent them from reaching as high values as the recording meter, which is more sensitive.

Reference to the curve sheet from the recording meter indicates the most severe conditions were imposed at full speed astern. On some of the backing tests the interruptions to the steady flow of the current were caused by the helmsman, when he saw no immediate indication of rudder travel on the helm angle indicator and believed that at the moment the motor was not moving. As a matter of fact, the motor was turning very slowly at the points of interruption until finally about the 22½ deg. rudder position was reached, when the motor accelerated quite rapidly. After

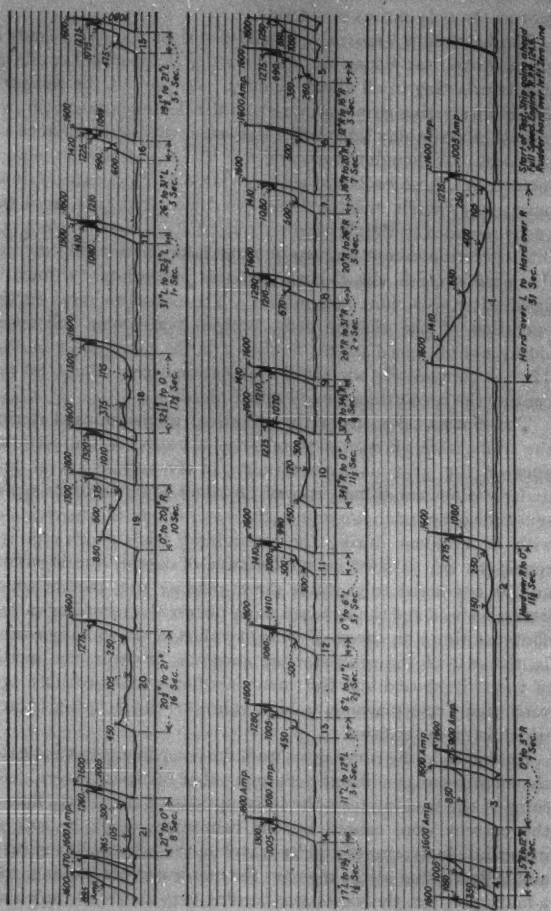

FIG. 12A—GRAPHIC RECORD OF TEST, 150-H.P. STEERING GEAR MOTOR, U. S. S. TEXAS

Tests made while off Cape Charles, Va.—Line volts, 120.

this the load fell off gradually as the rudder became more nearly parallel with the stream lines. When past the central position the water pressure against the rudder, due to the backward motion of the ship, actually assisted the motor.

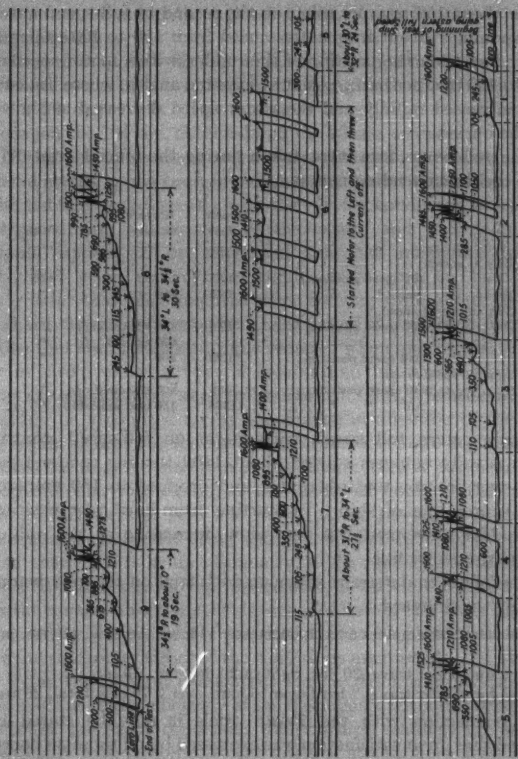

FIG. 12B—GRAPHIC RECORD OF TEST, 150-H. P. STEERING GEAR MOTOR, U. S. S. *Texas*

Tests made while off Cape Charles, Va.—Line volts, 120.

The rudder was turned from 20 deg. right to 20 deg. left, going full speed ahead, in about 16½ seconds, and from hard-over to hard-over in about 31 sec. The starting current on the direct-reading meters was about 1250 amperes. (The recording am-

meter at the same points indicated about 1700 amperes.) This refers to the full speed position with master controller thrown promptly to the last point. About 800 amperes were required on the first or slow-speed notch, which was also similarly indicated by the recording meter. On this slow-speed position the motor made about 150 rev. per min.; on the second or full-speed notch the running current frequently varied from 150 to 400 amperes, depending upon the position of the rudder, with a motor speed of 300 to 400 rev. per min., except at extreme angles, where the current increased rapidly and the motor speed decreased as shown by the curves.

The following data were taken during the official trial trip with the direct-reading meters:

	Ampere Peak	Ampere Steady	Volts
Ship at anchor			
full speed position	1220	150	120
half " "	1220	800	"
Ship full speed ahead,			
full speed position	1220	110 with stream	"
		400 against "	"
half speed position	1220	800	"
Ship full speed astern			
half speed position	1300	800 all conditions	"
full " "	1300	150 near amidship	"

Running astern full speed, with motor on full-speed control point, steady amperes started about 1100, turning rudder from hard-over position towards center, and dropped to 150 amperes near center line of ship. In starting from hard-over position the rudder movement was very slow, increasing as the rudder neared the center line.

The following data were taken on dock trial on the gear before leaving the shipyard.

Line volts 120; amperes max. 1200; steady 116; rev. per min. 410 (second notch).

Time for rudder travel 20 deg. right to 20 deg. left, 15 sec.

Time for rudder travel " hard-over to hard-over " 70 deg. total, 26 sec.

In connection with the *Texas* trials it may be stated in general that great satisfaction was expressed by all those on board at the results obtained. And if we assume that 1600 amperes as indicated by the recording meter was the maximum running current required (which is certainly high owing to the errors of the meter explained above), it will be noted, from the curves in Fig. 11, that this corresponds to 60 per cent overload on this 150-h.p. motor or 100 per cent overload on a 120-h.p. motor. It

therefore appears that there was considerable reserve power available for turning under the extreme conditions, and that the original motor calculations based on 120 h.p. as shown on curve sheet Fig. 10 would have been quite sufficient for the requirements. In connection with the time of 16½ sec. actually obtained to operate the rudder through the 40 deg., it may be stated that in the calculations the total time was taken as twice that required to travel from 0 to 20 deg. and no allowance made for the increased speed of the rudder in traveling with the stream lines from 20 deg. to 0. This accounts largely for the difference between the 16½ sec. obtained and the 20 sec. required.

From the above data and results obtained on tests of other installations it has been found that the power required to turn the rudder changes greatly with the varying conditions which will obtain during the steering of the vessel, and the deduction would appear to be warranted that the maximum torque required when moving the rudder from zero to hard over is greater than that required when moving from about 20 deg. to hard over after running for a brief period at the 20 deg. position. Also that the maximum torque required when moving the rudder from hard over to hard over is greater than that required for moving the rudder from zero to hard over. This, it is believed, can readily be accounted for by the change in direction of the flow of water against the rudder. If the rudder is at 20 deg. and the vessel turning, the direction of the stream lines is not nearly so perpendicular to the plane of the rudder as would be the case if the rudder were at zero and moved to hard-over, the hard-over position of the rudder being attained, of course, before the vessel had answered its helm. Similarly, if the rudder is at the hard-over position and moved immediately to the hard-over position in the reverse direction, the direction of flow of the water against the rudder is more nearly perpendicular to its plane than would be the case under either of the conditions mentioned.

From the above it is apparent that no definite deductions can be made as to the efficiency of the mechanism without taking into account the exact conditions under which readings are taken, especially with reference to the angle of stream lines against the rudder, as data taken under various conditions would seem to indicate an efficiency of the mechanism ranging from about 23 to 35 per cent. In the case of the *Texas* our assumption of 35 per cent total efficiency for the gearings was apparently very nearly correct.

The results obtained from various installations show interest-

ing facts regarding power required to move the rudder when backing. In the case of the *Mississippi* the backing test showed much more power to be required in backing than in going ahead. In the case of the *Texas*, however, the backing power is but little different from that required at full speed ahead, which we assume may be accounted for by a difference in balancing of the rudders for the two vessels, as a difference in the amount of rudder balance would naturally produce a difference in this respect. It is ordinarily assumed that the condition imposed in backing is much more severe than going ahead and the results obtained with the *Texas* on this point, are, therefore, especially interesting.

Conclusions

In conclusion, we believe that the results from trials and service operation of these several installations show that the results previously enumerated to be accomplished by the use of the electric drive have been fully attained. The popularity of the electric gear with those who have been concerned in its operation would seem to have been clearly established, and in addition to a saving in weight, space and efficiency, an ease and accuracy of control has been obtained which has not only eliminated all effort for the helmsman in steering the vessel but has enabled him to keep on the course with smaller and fewer movements of the helm.

The results on the *Texas* have shown that our calculations of the horse power required were fairly accurate and the results obtained have indicated that the capacity actually installed was more than necessary, and considering the fact that the rudder on this vessel was operated through the required 40 deg. in 16½ sec. instead of 20, which would have permitted a still greater ratio of gearing to have been installed within the requirements, it is apparent that had such a gearing been provided, a motor but little in excess of 100 h.p. rating of this type would have been sufficient for the work. This is in marked contrast to the size and rating of a steam engine which would be necessary for the same service. It may be noted also in this connection what a large proportion of the power is used in the operation of the screw gear itself, and where a more efficient type of gear is employed the motor horse power would be still further reduced.

In view of the above it appears to us that the electric gear is up-to-date and has come to stay and it does not seem, therefore, too much to predict that electricity will in the future be used generally as the power for the steering of vessels.

DISCUSSION ON "ELECTRICITY THE FUTURE POWER FOR STEERING VESSELS," (HIBBARD), NEW YORK, MAY 19, 1914.

G. A. Pierce, Jr.: We do not agree with the author that the American navy has been the most conspicuous exception to the limited use of electricity in marine work. In 1902 on the Russian battleship *Retvizan*, building at the time the U. S. S. *Maine* was building, the generating plant was 528 kw. compared to 328 kw. on the *Maine*. Remote control contactors were used exclusively in connection with turret turning, ammunition hoists, elevating and rammers, which at that time had not been contemplated in the American navy and only used to a limited extent in this country. Six-inch bilge pumps were operated by 60-kw. motors, six in number; electric steering gear; electrically driven forced draft fans; six-pounder and three-inch ammunition hoist operated by remote control—none of which was in use or contemplated at that time in the American navy. Furthermore, the step-by-step motion for interior communication apparatus, recently adopted by our navy, was used. The majority of the systems were copied from the French navy at that time. Prior to the adoption of electric heating in the U. S. navy ships, several merchant vessels were thus heated, not only in America but in England, and the extended use and development has been retarded owing to the lack of engineering in connection with these early installations. Electric steering gears, windlass and capstans and in fact, every use in which electricity is at present employed, has been previously used both in the merchant marine and in other navies.

While our recent achievements are very creditable, we should not look on them with too much pride.

Referring to the question of control of steam steering gears, I thoroughly agree with the author, particularly when I recall one installation in a cruiser with shafting from the pilot house to the steering engine room. When the vessel was loaded and maximum temperatures were reached after all fires in the boilers had been lighted it was impossible to move the shafting, and resort was made to the electric telemotor which previously had been installed as an auxiliary, and this electric telemotor was used to operate the vessel thereafter, although the system of shafting was made to operate with some degree of success. In most steam gears where hydraulic telemotors are used, it is customary to supply an indicator to tell when the transmitter and the receiver of the hydraulic system are in synchronism. This is required because of leaks in the system, and clearance in the pistons.

Referring to the results to be accomplished by electric steering, we do not agree with the author that the noise has been greatly reduced, especially with the system using contactors, as their constant operation is attended with noise. Furthermore, the electric control is not, in my opinion, the simplest means of control, as we can conceive of nothing simpler than the wire rope

transmitter with Hanscom drum for operating a steering gear, and any troubles are more easily traced and found than is possible with an electric gear, with all the electric wiring and circuits and its multiplicity of contacts.

Referring to the history of electric gears, we desire to take exception to the author's statement that in recent years, only, has the matter been given sufficient attention and the electric apparatus developed to such a point as to permit of successful results being obtained, and we point to the succeeding page of the paper for illustrations of early and successful steering gears, namely, Russian ships, and the *Finland*, *Minnesota*, and *Dakota*, and we believe these were not only some of the first, but the first successful electric steering gears used.

The remainder of the paper is devoted to the description of rheostatic control gears, and we note the author's remark "it is not the purpose of the paper to draw close comparisons between the features and merits of the various systems." We think, however, in view of some other statements in the paper, some further remarks relative to other systems are essential.

If we approach the question of electric steering gears from an engineering standpoint on the basis of the requirements laid down, we require the following:

A gear for frequent starting and stopping and for short movements to right and left of central line, for maximum torque regardless of speed, as the speed depends on the design of the gear used, easy starting and stopping to prevent wear, one with a minimum number of parts and contacts to become deranged. If a maximum of the above can be obtained in one gear the question of per cent efficiencies drops into insignificance, so long as the gear is not positively wasteful.

The speaker is of the opinion that the Pfatischer gear comes nearer the solution of this problem from an engineering standpoint than the rheostatic control, although, commercially, the rheostatic control may have some advantage.

The rheostatic control as applied to steering gears appears not to be the engineering solution of the problem. The line current with full line voltage for every movement is used with the resistance to control the amount of energy for the work to be done, and this seldom amounts to the rating of the motor when compared to the number of operations, and in that event a brake is applied to stop the momentum imparted. It should be noted that 20 seconds is usually the longest time run, and during this period to start the motor, eight or ten contactors are used to bring the motor to full speed, dynamic braking as well as disk braking to stop the operation and a limit switch installed to prevent overtravel.

The pumping of so large a motor is sure to affect seriously the voltage of the entire system, as we note from the curves, 10 peaks of 1600 amperes or 200 kw. in approximately two minutes.

Relative to the follow-up gear, it does not appear in the paper,

and we have never been able to obtain satisfactory explanation, what advantage is to be obtained by its elimination. It is an automatic stop for the system, as well as an indicator of the position of the rudder at all times, and when not installed its functions are supplemented by a rudder indicator which is very seldom installed on merchant vessels, and also by the automatic spring in the reversing switch on the bridge, as described in the paper, to operate in the event of accident to the helmsman. It is our opinion that the advocates of the non-follow-up system are misguided.

In conclusion, the electric steering gears as designed, installed and operated successfully for twelve years, have perhaps one-tenth the pieces of apparatus and one-thirtieth the number of connections of the gear advocated in the present paper, and as the author of the paper was intimately connected with the selection of the steering gear for the *New York* and *Texas* it would be interesting to know if the decision was reached on an engineering or a commercial basis.

Mathias Pfatischer: In regard to the criticism that a small Pfatischer gear as installed on the cruiser *Montgomery* requires a current consumption of 25 amperes at all times the rudder is not being operated, I looked up my records and found that the amount is about one-half of that stated.

As regards the difficulty mentioned of getting a sufficient operating voltage by the use of the Wheatstone bridge connection, I have never found such to be the case. As a matter of fact I could get about 40 volts on the third contact from zero, and nearly full voltage on the sixth point. I have found that for successful electric ordinary steering of a steamer not more than about 40 volts are required; it varies from about 10 to 40 volts across the steering gear motor armature terminals. Full voltage is required only on rare occasions. This indicates to me that a constant voltage system will hardly constitute a proper solution. I have found in my work in the past that the amount of power required for steering a straight course across the Atlantic is very small. On the Red Star liner *Finland*, which is of 10,000 tons and has a speed of 16 knots, the current consumption never exceeded 15 h.p.

I cannot agree with the author of the paper that the steering gear which he has described marks an advance in the art and believe it has never been tried out under adverse conditions, such as, for instance, in steering a ship through a crooked channel. It seems to me it is considerable of a disadvantage for the quartermaster to have continually to watch the rudder indicator, because it distracts his attention. He should be looking at the compass and the bow of the ship instead of the indicator. He should know that when he moves the steering wheel or pointer to say five degrees right or left that the rudder would move to that point and stop automatically, without his having to pay any attention to the rudder indicator so he may know when to cut off

the electric power. The gear described is not fool-proof, which a successful electric steering gear, in my opinion, must be.

Maxwell W. Day: In referring to the systems using motor-generator sets, criticism has been made concerning the weight, size and cost, but there are certain advantages which should not be overlooked.

1. It has been shown that the starting peaks on the *Texas* gear amounted to 1600 amperes with a 150-h.p. motor. With a 350-h.p. motor these peaks would naturally be taken up to over 3700 amperes for a 120-volt ship, and further, the more rapid movement of the rudder from hard over to hard over will increase the working load more than in this same proportion. Mr. Hibbard has called attention to the fact that when the ship is turning from one extreme position to the other, the rudder requires greater power than when the rudder is moved from midship position to the outboard position.

In some tests made in the German navy a few years ago, it was found in going from hard over to hard over that the maximum pressure was obtained at about 30 degrees rudder position, instead of 38; the pressure being 71 tons at 30 degrees, while the pressure calculated from Middendorf's formula for 38 degrees shows 35.5 tons. On this account, a steering gear to operate at the high speed required on the recent ships, will require more than twice as much power as if the rudder were to move at one-half the speed.

On this account, the rheostatic system for some of the later ships would require contactors capable of operating with 4000 to 4500 amperes, and this, in itself, is a serious problem. If the use of these large contactors is to be avoided by the use of two motors, each of one-half capacity, a much larger number of contactors of smaller size is required, and the system of connections and interlocks becomes very complicated, especially if a series-parallel or parallel-series arrangement is to be used.

With a motor-generator, the contactors required for starting up the motor-generator set are very few in number and seldom used; so that the conditions for the few contactors required are very much more favorable.

2. With the rheostatic system a heavy peak of current is occasioned at the instant of starting and a large amount of energy is dissipated in the starting rheostat every time the motor is started. With the shunt motor the energy lost in the rheostat is practically equivalent to the kinetic energy of the armature at the speed required at the time the rheostat is completely cut out of the circuit, and with a compound motor somewhat less.

This is not mentioned on account of the question of efficiency, as the running-light losses of the motor-generator set probably just about offset it, but this system of starting requires a heavy load to be put upon the generating plant, practically instantaneously, and as the rudder in many cases is moved four times a minute, this produces a sudden fluctuating load upon the generat-

ing plant, which is objectionable from an operating standpoint, and criticism of this has been made in some cases. On the other hand, the motor-generator system avoids these peaks, because the motor is started up without the insertion of resistance, and the load is gradually applied to the motor by the building up of the field of the generator, and during the time that the rudder motor is operating at low speed, and requiring a correspondingly low voltage from the generator, the power taken from the generating plant is relatively small.

In addition to this, the compound winding of the motor-generator set slows down the speed as the load is applied, thus transforming a portion of the kinetic energy for the accelerating of the rudder motor armature.

3. As the rudder torque increases very rapidly as it is moving away from the midship position, it is desirable to increase the torque per ampere of the motor, which is done in the rheostatic system either by using a compound-wound motor or by automatic strengthening of the field of a shunt motor, but in addition to this feature, the generator of the motor-generator system is provided with a drooping characteristic by means of a reversed series winding, so that the amount of power required is very much reduced, and this same effect is increased by the compound winding of the motor of the set, which reduces its voltage still further by reducing the speed of the generator. In this way, the power taken from the generating plant is increased at light loads and reduced at heavy loads, to a greater extent than is available with a compound motor, working on a constant potential system with rheostatic control.

4. Further, with the rheostatic system, the stopping of the rudder motor armature is accomplished by a dynamic brake and a mechanical brake, so that the kinetic energy of the armature is transformed into heat; but in the case of the motor-generator system, a considerable portion of this energy is stored up again in the increased speed of the motor-generator, and will be available for use at the next time that the rudder motor is started.

What has been said concerning the motor-generator system, applies, to a considerable degree, to a separate generator operated by its own prime mover, except that with a regulating governor used on generating sets, the speed of the generator will be practically constant, and therefore, does not have the same advantage in storing up kinetic energy at increased speed.

5. Reference has been made to the Pfatischer system. This system is provided with a follow-up control. It has the advantages mentioned above as applying to motor-generator sets or separately driven generators, and has the further advantage that it allows the use of an extremely simple type of follow-up control.

Reference has been made to some of the Russian ships, and in this connection I will mention that the Russian cruiser *Pallada* and German cruiser *Aegir* were equipped with the Essberger gear. This consisted of two shunt motors running in opposite direc-

tions, connected to differential gearing. When the motors are running at the same speed, the rudder remains stationary. When the speeds are changed by shunt field control, one motor running faster and the other slower, the rudder is moved at a speed corresponding to the difference of the motor speeds.

These equipments do not have a follow-up control, and the German equipment was taken out, as it operated in a manner different from that of the customary steam gear.

R. A. Beekman: There are some values of current given in the paper under "Ampere Peak" and "Ampere Steady." Under "Ship at anchor, full speed position," the "Ampere Steady" is given as 150, and at "half speed position" as 800. I would like to know how the 800 came about.

H. L. Hibbard: That is because in the slow-speed position there was an armature shunt connected there, which allowed the current to pass around.

Mr. Pierce referred to the large number of installations effected on the Russian battleships some years ago, and I wish to explain that in the part of the paper in which that reference is made, I intended to convey the idea that the marine field in general was one of the least developed of any, that the American navy had developed this field more than the merchant marine in this country, and in my belief we had progressed further in the electrical field in the navy than any other nation in the world.

Mr. Pierce also asked what are the advantages of the elimination of the follow-up. In the first place a very decided advantage in the elimination of the follow-up is the simplification of the apparatus itself to the bridge; the control itself is thereby very much simplified. I think the control with the non-follow-up type is quite as simple as the Hanscom drum, and not any more liable to give trouble, consisting, as it does, of one lead of cable containing three or four small wires, probably in one-inch conduit, and the contacts at the master controller are few, small and substantial.

In the second place, by the elimination of the follow-up system it has been clearly shown from the results that the response which is obtained is a little more rapid, and that the man at the helm does not have the same tendency to be moving the master switch as he does with the old wheel. In that case there seems to be a tendency for a man to move the wheel back and forth, whether any movement of the rudder is produced or not. Results, however, with the master switch control, of the non-follow-up type, show that he moves the wheel or lever only when he wants results, and he furthermore does not have to steer as much; that is, he can keep his ship on the course with fewer movements of the helm, owing in part to the very rapid response with this type of control.

As to whether the *New York* and *Texas* steering systems were decided on a business or engineering basis, of course, both business and engineering is involved in all these matters. In

the case of the *New York*, the lowest bidder obtained the contract for the installation of the apparatus, so that fact eliminates the question entirely as to whether it was decided on an engineering or a business basis. No matter which system was the low bidder, it would probably have been installed; that is, either of these systems was acceptable for these ships, and, therefore, they were on a free competitive basis as regards the business end of it.

As to the question of the *Texas*, I think I can say that the installation, as made, was not effected on a business basis, only, by a large percentage. Engineering considerations had a great deal to do with it.

Mr. Pfatischer has mentioned an error, apparently, that has been made in the amount of current consumed in the motor-generator set. I have simply to explain that the figures given there were furnished by a representative from the navy department, as secured from the *Montgomery* set, and if I am mistaken I will be glad to accept the correction.

As regards the use of the non-follow-up type of gear in harbors, etc., I think experience has shown that a man can steer in a harbor quite as well with non-follow-up as he can with the follow-up system, after a little experience, and that he seldom needs to look at his indicator, does not need to know where his rudder is, and when in the harbor, can look on either side of the vessel, and see that he does not run into anything. I have stood beside a master switch and watched the helmsman, and find that it is only a question of watching the bow of the ship, or objects on one side or another, and he does not need to care where the rudder is. When the ship is at sea, and they are steering on a straight course, it is usually a question of watching the bow of the ship and the compass. When the vessel is in fleet maneuvers or formations of that kind, it is important to know where the rudder is, and the indicator is then necessary.

With regard to starting peaks, which Mr. Day has referred to, and Mr. Pierce also, I will say since the paper was written, that on both the *New York* and the *Texas* the arrangement of connection and resistances has been changed. We found it was unnecessary to have such high starting currents or the armature shunt connection, so that the starting peaks, instead of being 1500 or 1600, as shown on the curve, are now 800 or 900, and as regards the load on one generator, or any number of generators, our trial of the *Texas* showed that even with the high peaks which were obtained, one generator could be used with the lighting load, and only a slight fluctuation in voltage beyond the normal noted. With two generators no change in voltage was noted, and with the reduction in peak one generator can readily be used without any fluctuation in the voltage.

As regards the 4000 amperes required for the contactor system, I will say that Mr. Day has himself already explained that to some extent. On one of the recent naval installations two motors have been installed, as stated in the paper, and the power

divided, so that any contactor does not carry more than about 1000 amperes as a maximum. The two motors are instrumental in cutting down the peak rushes of current, and minimize the amount of power required at the smaller angles, at cruising speeds, etc.

As regards the dynamic current required in stopping motors, I would say these motors are especially selected, and operate at low speed, that is, comparatively low, and it has been found that it is quite possible to stop the motors without the use of the disk brakes at all, if you wish to depend to that extent on the dynamic effect. It is not so necessary to stop the motors quickly when the non-follow-up system is used. When the follow-up system is used, you must stop them with the quicker acting dynamic brake, to prevent any possibility of following over.

As regards the two systems in general, there is no question but that the rheostatic system may have a few more small parts, while the motor-generator system certainly has a greater number of large parts, and the weight is much greater, and, of course, the first cost, which may be incidental, is greater. There are of the two systems now sufficient installations being effected so that in a short time we will have results of the total power consumed by the two systems, and it is my prediction that the rheostatic system will show a total consumption over a considerable period of time appreciably less than the motor-generator system.

H. A. Hornor (by letter): The advantages of the contactor type of steering gear control have been clearly set forth by the author of this excellent paper. The disadvantages may be briefly stated as follows:

Contactors may be prevented at times from properly functioning due to the rolling and pitching of the vessel.

They may also be affected by the vibration of the vessel, which at high speeds in this location is often very severe.

In general the mechanical as well as the electrical wear and tear on this type of apparatus occasions very careful supervision and upkeep.

The current demands on the generating plant are too great and too frequent. The latest requirements for the design of generators for naval service state that, for 300-kw. sets, the speed variation must not exceed 4 per cent when full load is thrown on or off; and 3 per cent when load is suddenly varied from full load to 20 per cent of full load, or vice versa, when operating condensing at normal steam pressure. The jump in voltage must not exceed 12 per cent, or 15 volts in the case of a 125-volt machine, when full load is suddenly thrown on or off, under all the varying conditions of steam and operation. The author of this paper gives ammeter records for a 150-h.p. motor, 60 per cent overloaded. Current peaks of 1600 amperes in short variable periods of time are indicated. This represents 3/4 load for one 300-kw. generator. In the case of a proposed 300-h.p. outfit this would mean full-

load current peaks of 2100 amperes, or nearly full load for one 300-kw. machine. If 100 per cent overload is demanded, the current peaks would double, requiring full-load current from two 300-kw. generators; or the full load capacity of the after dynamo room. There would remain for the general supply of current to the ship 1600 amperes, or the 1/3 overload capacity of the two generating sets. Under practical working conditions on shipboard the jump in voltage averages about 10 or 12 volts—an amount which will affect the lighting and perhaps other installations.

The disadvantages of the motor-generator control are mentioned in the paper and therefore the advantages will be stated:

No contactors in continual operation.

Reliability insured by staunchness of design.

Reduction of supervision and upkeep.

The omission of the electro-mechanical brake.

Reduction of current peaks, thereby cushioning the loads on the generating plant.

Presented at the 295th meeting of the American Institute of Electrical Engineers, New York, May 19, 1914, under the auspices of the Committee on Use of Electricity in Marine Work.

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THE FUTURE OF ELECTRIC HEATING AND COOKING IN MARINE SERVICE

BY H. J. MAUGER

ABSTRACT OF PAPER

Indications of the future point to electric motor-driven propulsion and abandonment of coal-burning boilers. Electric cooking and heating is in line with this development and the source of heat for cooking and heating will be confined to the boiler room. The future of electric cooking apparatus is assured by the progress already made in the U. S. Navy in adopting electric equipment. Detailed report is given of trial trip of U. S. S. *Texas*, which depends almost entirely upon electricity for cooking. Consumption of 1.25 kw-hr. per person per meal is indicated. Load factor was 50 per cent.

Electric ranges and bake ovens effect considerable saving in weight and space and release cooks from being "firemen" to devote their time and effort to good cooking. Electric cooking finds greatest advantages in high temperature cooking.

Electric heating on shipboard does away with the disadvantages of steam piping and gives individual and local regulation and provides, where desired, glowing heat without fire.

Other accessories are the electric flatiron, the soldering iron and therapeutic devices.

IF we may be permitted to look into the future five or ten years, we venture to make the forecast that first-class vessels will be driven by electric motors, direct-connected to the shafts of the propellers, the electricity being generated either by steam turbine-driven generators, energized by steam furnished from oil-burning boilers, or else by electric oil-generator sets.

In assuming the role of a prophet, we naturally enjoy the freedom of a wide latitude and place ourselves beyond the sphere of criticism, but we believe that the members of this Institute will agree with us, at least, that signs point in that direction.

On board ship, very important, if not paramount, are the considerations of saving in space and weight, as well as considerations of cleanliness and convenience and despatch; and nothing that we know of at the present time so completely and satisfactorily meets these requirements for their purpose as the electric range and bake oven, with their culinary accompaniments, on the one hand, and the electric air heater on the other, not to

speak of such miscellaneous applications as the flatiron, the soldering iron, etc. In other words, in our vision of the model ship of the future, we can see no other source of heat and power than electricity, outside of the boiler or engine room.

When we realize that a number of the U. S. battleships, not to speak of submarines and army transports, recently constructed or in process of construction, have adopted electric cooking and heating in full or in part after the most thorough investigations, extending over a period of years, electric heating and cooking in marine service becomes an established fact, and it remains only to see what the future may bring forth.

Among battleships which have been partly equipped with electric cooking and heating are the *Arkansas* and *Wyoming*. The battleships *Texas*, *New York*, *Nevada* and *Oklahoma*, which are now under construction, have the galleys and bakeshops completely equipped. Already thirteen submarines have been equipped entirely, and eight more are in process of construction.

The *Wyoming* has three electric ranges in the officers' galley and electric cooking is there used exclusively; in the crew's galley, there are four electric ranges and four coal ranges. The *Wyoming* was equipped with the latest design of ranges December 24th, 1912, and has had no appreciable trouble, except with the hot plates of the cooking surface, which has since been overcome.

Recently the army transport *Thomas* returned from Manila carrying about 1500 troops and crew. Two type D-47 bake ovens, capacity 108 one-pound loaves, proved sufficient to bake all the bread, pastry, etc., required, although three ovens were available. No trouble was experienced, and everyone interested was pleased with their operation.

Of special interest is the recent trial trip of the battleship *Texas*, made during last October, because for the first time a large number of men (715) at sea were entirely dependent upon electric cooking for their daily meals. During the run of two weeks, there were no breakdowns of any kind and the cooking was done in a perfectly satisfactory manner.

The results of this trial demonstrated that the equipment was more than sufficient to take care of the ship's full complement, which will comprise about 1070 men, including 70 officers. This ship's equipment consists of 15 electric ranges, type D-48, and 2 bake ovens, type D-50, and with the exception of some

supplementary steam kettles and coffee urns in the crew's galley, there is no other means of cooking or baking available on this ship. The success of the trial is all the more apparent in view of the fact that none of the cooks had any previous experience in using electric apparatus and that they so readily became acquainted with its operation and had no difficulties in performing the duty required. The attendants, without exception, were pleased with the performance of the electric ranges, as well as the bake ovens, being much impressed with their greater efficiency and cleanliness.

The trial trip of the *Texas* is also significant because for the first time has it been possible to obtain such complete and valuable data.

Five ranges are installed in the officers' galley, four of which were in daily use; and in the crew's galley there are ten ranges, six to eight of which were used daily during the trial, as well as two bake ovens in the bakery. The officers' galley served 162 men and the crew's galley 553 men; a total of 715 men. The ovens proved to be of sufficient capacity to supply a crew twice as large as that aboard, and they were perfectly suitable for all kinds of work demanded of them. The officers' galley was in use from 6 a.m. to 9:30 p.m. (except an hour and a half from 2:30 p.m. to 4 p.m.). A few hot plates were kept in service at all times, supplying hot coffee. The crew's galley generally was in use from 4:30 a.m. to 8:30 a.m.; 10 a.m. to 1:30 p.m.; and 4 p.m. to 8:30 p.m., depending somewhat on the daily menus.

Referring to Fig. 1, the top curve shows the daily cooking load, in kilowatt-hours, which averaged 1258.6, the highest daily load being 1695 and the lowest 806 kw-hr. The downward slope of the curve shows a radical increase in economy as the cooks became accustomed to the use of the electric ranges, and the economy would be still further increased by longer experience. This consumption proved to be an average of 1.7 kw-hr. per person per day for the total; but further reference to the accompanying curve shows that the average total consumption of the crew's galley (556 kw-hr.) was only slightly more than that of the officers' (519 kw-hr.). The average consumption per man per day of the crew's galley was one kw-hr. as compared with 3.2 kw-hr. of the officers. The average daily consumption of the bakery was 182 kw-hr. total, or 0.25 kw-hr. per man. Without doubt, the total consumption for cooking and baking should not average more than 1.25 kw-hr. per day per person, instead of 1.7 kw-hr.

In accounting for the difference of the energy consumption per man in the officers' galley as compared with the crew's galley, we have to consider that there is no steam cooking in the former and this would account for 25 or 30 per cent of the total consumption. It should be further noted that the officers' galley was operated somewhat on the plan of an *a la carte* or

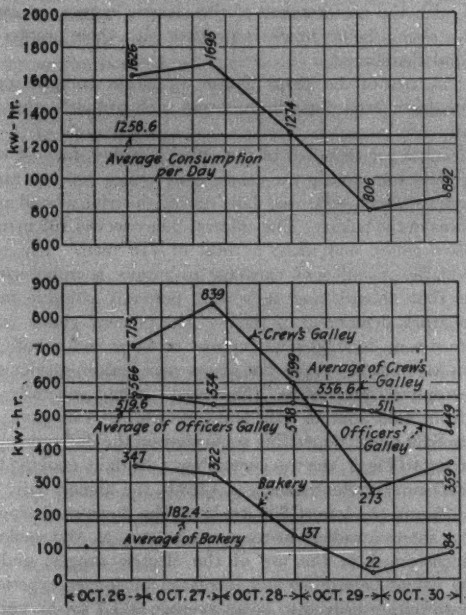

FIG. 1—TRIAL TRIP OF U. S. S. *Texas*

Total current consumption of electric ranges in bake ovens Oct. 26 to Oct. 30, 1913, inclusive. Officers' galley served 162 men; crew's galley 553 men; bakery served 715 men.

European plan restaurant where the meals were strung out over longer periods—more severe service than will actually be required when in commission; while in the crew's galley, advantage accrued from cooking for a much larger number of men at one time. Reference to the menus shown in the curves will indicate that the crew fared very well.

Fig. 2 shows the load curve for the ranges in the officers' galley on Oct. 30th, in which the total consumption was 451.7 kw-hr. The average kilowatt demand was 27.4 while the maximum (during the dinner period) reached 54 kw-hr. Four

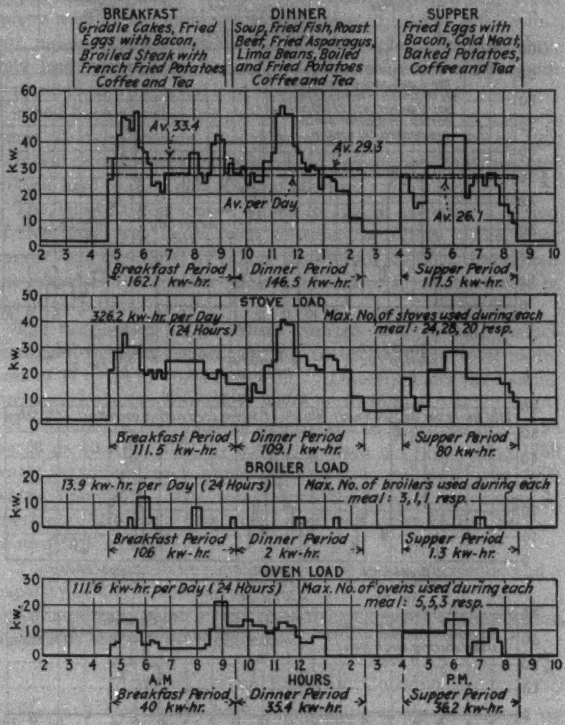

FIG. 2—TRIAL TRIP OF U. S. S. *Texas*

Five ranges, 162 men—energy consumption of electric ranges in officer's galley October 30, 1913, (24 hr.) 451.7 kw-hr.—coffee and tea are kept hot af all hours.

ranges were in actual use in the preparation of this meal. The load factor, taking it as the ratio of the average to the maximum demand, was, therefore, about 50 per cent. The ratio of the maximum demand to the connected load (used) was 54 to 120.

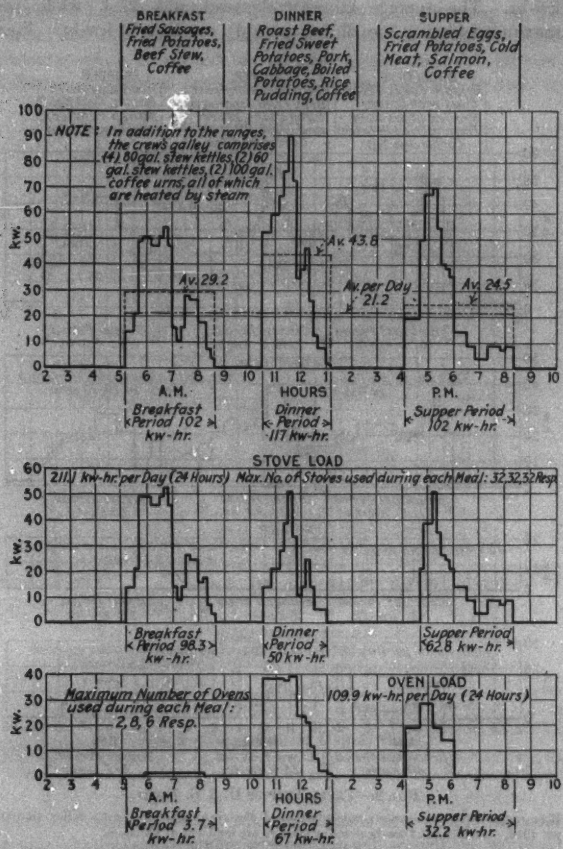

FIG. 3—TRIAL TRIP OF U. S. S. *Texas*

Ten ranges, 553 men—energy consumption of electric ranges in crew's galley October 29, 1913, (24 hr.) 321 kw-hr.

The curves in Fig. 3 show a daily load curve for the ranges in the crew's galley indicating a total consumption of 321 kw-hr. The average demand was only 21.2 kw. and the maximum was 90 kw. (during the dinner period), making a load factor of about 24 per cent. Though there are ten ranges installed, only eight ranges were in use, making a total connected load of 240 kw-hr.; but, judging merely from the number of hot plates used that day, only four ranges were necessary. The ratio of the maximum demand to the connected load was, therefore, 90 to 240; whereas if it had been possible for the cooks to operate so as to use each range at its maximum, the ratio would have been 90 to 120.

It will be interesting for comparison here to note that the total electric load of the *Texas* is about 600 kw.

The kilowatt-hour curve shown in Fig. 1, covering a period of five days, was taken from wattmeter readings. The other curves were computed by taking ten-minute readings throughout the period of the number of hot plates, ovens, etc., that were in use at each time.

The range used on the *Texas* consists of a cooking surface composed of eight rectangular hot plates having a total useful area of 37 by 24 in. (0.93 by 0.6 m.). Directly under the cooking surface are the two broilers 18 by 24 in. (0.45 by 0.6 m.). Below the broilers are two roasting ovens each of which is 18 by 28 by 16 in. (0.45 by 0.71 by 0.4 m.). Each hot plate takes 1750 watts maximum; each broiler, 4000 watts, and each oven 4800 watts, maximum. The total connected load of the range is, therefore, 31.6 kw. One range oven will roast 75 lb. (34 kg.) of meat at one time.

The bake ovens have a consumption of 16 kw. maximum and a capacity of about 100 loaves.

An important point is that all heating elements of the cooking apparatus are readily replaceable.

Advantages of Electric Cooking

We shall now sketch briefly an outline of the conditions on board ship which we expect to see realized in the near future.

Compared with the old-fashioned, coal-burning, brick oven, the electric oven shows a most decided advantage. The electric oven will require only two-thirds the time to be heated up to baking temperature. The only effort required from the baker being a turn of the switch, his time and energy, therefore, can be entirely devoted to its proper purpose,—baking good bread for

passengers or crew. And we must not forget that he will be further aided by motor-driven dough kneaders and other modern bake shop conveniences. There will be no excuse for slack-done or over-done bread or no excuse for stale bread or lack of bread,—as the electric oven will need no attention but an occasional turning of the switch to "high," "low" or "medium" as may be required. The electric oven will not demand any shifting of the loaves in the oven to give some of them the advantage of a hotter place or relieve others from burning, a matter which not only dissipates the cook's time and attention but also considerable heat while the doors are open. Furthermore, one electric oven will do the work of two coal ovens and with more than a corresponding saving in space and a very much greater saving in weight.

The temperature of the bakery will not be appreciably increased as formerly from the waste heat of the radiating brick of the coal oven and the baker's temper and his bread should be as good in the tropics as in the arctics.

What has been said regarding the ship's oven also applies with similar force to the ship's range. Here the compartment previously devoted to the fire and ash box is devoted to an extra roasting oven, increasing the roasting capacity 100 per cent, besides adding special broiling space which provides for two broiling compartments. There is not, of course, much opportunity of increasing the utility of the range top, all of which was formerly active as a cooking surface.

Saving space formerly required for coal boxes, eliminates fuel or ash handling and, therewith, danger from fire or explosion. Absolutely uniform temperatures are secured by the electrical method.

One of the chief advantages in the electric range lies in the broiler, which the coal range entirely lacked. Broiling, like toasting and similar operations, requires a very high degree of heat which should be in the nature of radiated heat from a red hot source; lower temperatures will give the effect of roasting or baking. The coal range often has been the despair of the cook when he wished to do broiling, for that operation required just the right condition of the coals, which is difficult, if not impossible to secure when desired; but the "electric" cook simply turns the switch and instantly the electric coils glow with radiant heat and the sizzling steak at once responds to the broiling operation. Broiling in the coal range also interfered seriously with other

cooking on the stove top. The broiler will also often be useful in browning the products of the oven and, indeed, will be used as a toaster.

The appliances we have described are chiefly used for what we may call high temperature cooking operations—broiling, toasting, roasting, baking, frying, grilling, rapid boiling, etc.—and, of course, it is in this direction that electric cooking finds its greatest advantages.

There will be considerable reduction in the depreciation cost of high temperature cooking appliances, as it will no longer be necessary to renew fire boxes, etc., or oven linings and stove tops, because the electric ranges will not *overheat*.

Advantages of Electric Heating

The problem of heating staterooms, cabins and saloons by electric heating will be solved by two general forms of heaters, both having the same advantage of perfect control and both effecting a saving in space and weight over that taken by the old style steam piping, not to speak of the absence of leaking, sizzling and pounding steam. Furthermore, there is an advantage in low initial cost, as well as in installation and maintenance cost, besides the feature of portability. This feature not only adds to convenience, but may often enhance the warmth and comfort of the occupants of a room. One of the most important advantages, however, lies in being able to regulate the amount of heat desired, accommodating atmospheric conditions or personal requirements. Overheated atmosphere may be worse than cold and an open window or porthole impractical if not risky.

The two methods are the direct air heating and the luminous. The former is especially adapted to the heating of larger spaces where the air can be circulated over electrically heated coils at moderate temperatures. The ideal electric air heater will have a low operating temperature and a large radiating and proper deflecting surface; the former to avoid any fire risk and the latter to produce a more uniform distribution of heat throughout the room by heating to a less degree a larger amount of air at one time, and to more effectively heat the lower strata of air. The method of heating, itself, is precisely that of the old steam radiator without, of course, any disadvantages already referred to.

The other form of air heating, the luminous method, can only be safely secured on shipboard by electric means. This has the advantage, but none of the drawbacks, of the cheerful glow of the

open fireplace, or the comfort of the sun bath. The radiated heat energy does not heat the air directly, but passes through it, giving up its genial warmth to the material object it strikes. The luminous radiator gives its maximum heat instantly upon the turn of the switch. Indirectly, of course, the atmosphere will gradually become heated from its use, but *instantly* a person may be warmed by coming within the range of its glow. It is, therefore, the ideal heater for the stateroom or the bathroom and for auxiliary use in the larger gathering places.

The luminous radiator will, undoubtedly, consist of a specially made incandescent lamp as a heating element; designed, however, for low *luminous* efficiency but for high *thermal* efficiency, emitting a large percentage of infra-red radiations.

Other Electrical Accessories

Perhaps a word should be said in passing for the electric flat iron in the laundry and the soldering iron in the repair shop, because as a matter of fact these are in general use and their convenience and success have really been an entering wedge for the adoption of electric cooking and other electric heating on shipboard. On the therapeutic side, the ship's surgeon will find in the electric hot water supply, the instrument and bandage sterilizer, and body heating pad, convenient aids.

Conclusion

In conclusion, it is our belief that all the handling of fires, of coal and ashes or oil, if done at all, should be done where it belongs, down below in the boiler room, not in the galley; and by the stoker, not by the cook. A contented state of mind, whether on the part of passengers or crew, is highly desirable on shipboard; and when the electric cooking has become generally adopted on shipboard, this will be largely assured through well and more easily cooked meals.

DISCUSSION ON "THE FUTURE OF ELECTRIC HEATING AND COOKING IN MARINE SERVICE," (MAUGER), NEW YORK, MAY 19, 1914.

W. S. Hadaway: In reading this paper of Mr. Mauger's, the first omission that strikes me is the practical elimination of the electric laundry on board ship. It has been my experience that the adoption of electrically heated laundry machines, such as body ironers, combination ironers, as well as hand irons, is an essential part of the equipment for the comfort of the men on an extended cruise.

When it comes to electric cooking my opinion is that the problem is not as simple, and that the solution is not as complete, as would be indicated by the results stated in this paper. I think I can say that the paper is based largely on the trial trip of the *Texas*, plus a considerable amount of optimism.

As I recall the specifications used by the department, they were put out in 1910, and bids for apparatus have been asked for under them several times. The contractors who have bid under these specifications thus far have had to pay very dearly for their experience.

So far as the oven is concerned, the electric range can be made a complete success. I want to call your attention, however, to the fact that the ovens referred to there are equipped for an input of 1 kw. per cu. ft., which is an extremely high input, considering the input which well-insulated ovens are figured to have. My information shows that the average oven in the market runs more nearly 0.8 kw. than 1.00 kw. per cu. ft.

When it comes to the broiler, I believe the author is entirely correct in saying that the present radiant unit for broiling and toasting is entirely satisfactory. The only point where the electric range falls down, and falls down good and hard, is on the top surface cooking.

You will note that useful area for top surface cooking is given approximately as 37 by 24 in. It is my understanding that these top surfaces are made up of a series of eight plates, each of which is 9 by 12 in. On the basis of an input of 1750 watts per plate, this would make the input per square inch approximately 18 watts. It has been the result of experience that a density of 18 watts per square inch represents approximately only one-half the rate of work which can be obtained by the ordinary coal range. Furthermore, the temperature at which the electric hot plate works is so low, compared to the coal range, that the service obtained from the electric range is wholly unsatisfactory.

My own experience in this line of work dates back to 1894, twenty years ago this summer, when we made an installation on the receiving ship *Vermont*, then lying at the Brooklyn navy yard. At that time the galley attendants were all Japanese, and the ingenuity which they showed in their endeavor to

make that stuff work was amazing. They wanted it, but they could not get the work out on time, and we had to take the apparatus out.

The same sort of an equipment was in use for about eighteen months after that installation had been made, in the offices of the manufacturing company, and wattmeter readings of the work done were kept, as well as records of the number of people served, and it was found that the input per person per meal was somewhat less than the figures given by the author.

As to my experience with the electric cooking proposition, I would say that there is no doubt as to the perfect success of the electric baking oven. I call attention, however, to the Navy specification which permits a loss of 40 watts per square foot, indicating heat insulation values which are relatively low—in fact, so far as I have data at hand for the moment, somewhat lower than we obtain in average practise.

The future of this work, it seems to me, is based solely on whether we can devise a durable structure that will do top surface cooking, such as frying, boiling, in small utensils, in a manner which will approach the results obtained on the older types of apparatus. It is too much to expect to get chefs, or people of that order of intelligence, to change the method of use. We have got to supply heat in relatively large volumes at high temperatures and make the apparatus speedier. The development of the chrome-nickel resistor makes this possible. The difficulty in doing it, however, is the added load which we place upon the generator plant. In other words, if we raise the top surfaces up to the point where they would compare directly with the coal range, we would increase the watt capacity, the connected capacity of the range, from 31.6 to 45.6 kw.

E. F. Dutton: There is one point I think should be considered, and that is the quality of the baking. It has been the experience, I understand, on shipboard, that the product is so much better, and the waste is so much less, that this fact goes very far toward overcoming other apparent disadvantages of the electric cooker.

Of course, the first thing that is spoken of in looking at a galley is the cleanliness of the galley, and that is one of the inherent advantages of the electric range or oven.

H. J. Mauger: I think Mr. Hadaway's remarks are very much to the point, and he, like ourselves, would like to have hot plates that would be more rapid. I think, however, Mr. Hadaway has kept that figure of watts per square inch in his mind more than is necessary. I remember a paper that he read before the American Institute of Electrical Engineers some time ago in which he brought out the fact that a gas flame would develop 40 watts per square inch, whereas up to that time the usual hot plate that it was safe to design consumed around 10 watts per square inch. But in a coal range

on board ship the cooking top does not become equally hot. It is only over the coal box that it is hottest, and we have not found any complaint from the cooks on the score that Mr. Hadaway points out, that the cooking is any slower than by the coal method. Even with only 16 watts per square inch, it seems to be satisfactory for present purposes, and there are developments in the art which will soon enable us, doubtless, to go beyond that.

Mr. Hadaway referred to the development of the chrome-nickel alloy, which gives a remarkably fine resistor, but it is in the application of that resistor that we find our practical limitations. We have got to insulate that resistor electrically with something, and the thing usually used is mica. Mica dehydrates and breaks down at around 700 to 800 deg. cent., depending on the quality and the character of the mica, so that makes a limitation in that direction; one that prevents our operating at a higher temperature. But I think that when the hot plates are applied as in the range the heat is drawn from more than one plate into the vessel in which the cooking is being done, each hot plate contributing its heat—and in that way makes up for any theoretical lack in watts per square inch under the vessel, so that the cooks seem to be able to get the same results as with coal or gas.

Doubtless on the question of thermal insulation much can be done and much more will be done. I might say that there is a domestic range just recently on the market, having an oven which has remarkable thermal insulation, in which the current is cut down to about half of what was formerly required. However, the larger the apparatus, the less relative radiating surface there is in proportion to the power that is used, so that the question of saving a few watts is not so important as it is when you are trying to cook in your own kitchen, at the lighting rate, within the means of your pocket-book.

Frank T. Leilich: The advantages of electric heating and cooking as set forth by Mr. Mauger can hardly be questioned. However, when viewed from the standpoint of cost, such applications of electricity can hardly be said to possess obvious advantages.

Aside from the illogical procedure of converting the heat energy of fuel into mechanical energy which is in turn converted into electricity and this finally transformed into heat, the electric range and oven are open to the following very serious objections:

1. High first cost.
2. High cost of repairs.
3. High operating cost.

The first and second objections may become less serious in view of possible improvements in manufacture of the apparatus. From the present outlook the third will, however, become of still greater importance than at present, owing to the increasing price of fuels.

As a matter of fact the fuel oil range is coming forward as a most serious competitor of the electric apparatus. The former combines relative cheapness of first cost with low cost of operation and ease of control. On the Pacific coast there are in operation a number of highly successful installations of oil ranges. Low pressure oil delivery is used in most instances. The most serious objection to oil is the fire risk, but with reasonable care and a well-designed installation the danger becomes a secondary factor.

The best steam plants convert not over about 16 per cent of the heat energy of fuel into electricity, and with the Diesel engine, the most efficient prime mover known, not more than about 30 per cent can be converted. It does not seem unreasonable to suppose that an oil range can be made in which at least 40 per cent of the heat of combustion is available at the heating surfaces.

Assuming a ship with a crew of 1000 men and taking Mr. Mauger's estimate of 1.25 kw-hr. per man per day as the requirement for electric cooking, the daily costs of electric and oil operation would be about as follows

1250 kw-hr. of electricity at 1.0 cent .....$12.50.
83 gal. of oil at 4.5 cents.....3.74.

The oil consumption is based on 40 per cent efficiency of the range and a B.t.u. requirement per day per man equivalent to that produced by 1.25 kw-hr. The heating value of the fuel was taken at 18,000 B.t.u. per pound.

If repairs and investment costs are considered, the oil range will make a still better showing than indicated by the above figures.

Presented at the Seattle Section meeting of the American Institute of Electrical Engineers, Seattle, Wash., May 19, 1914.

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EFFECT OF ELECTROLYSIS ON THE COMPRESSIVE STRENGTH OF CEMENT AND CONCRETE

BY C. EDWARD MAGNUSSON AND B. IZHUROFF

ABSTRACT OF PAPER

A paper on "The Electrolytic Corrosion of Reinforced Concrete", by C.E. Magnusson and G. H. Smith, was read before the A. I. E. E. June 30, 1911, and, as stated in that paper, the results could not be pronounced entirely conclusive, as the duration of the experiments was only 30 days. In the present paper a similar series of experiments is described by the authors in which the tests were continued for several months. The paper gives in tabular form the results of a large number of experiments and the conclusions corroborate the results reported in the former paper.

For the current density covered by the experiments, the current was found to produce no change in the compressive strength of concrete cubes, from which it is deduced that the failures of reinforced concrete due to electrolysis are due entirely to the forces produced by the increase of volume when iron is changed into iron oxide, and not by any direct action of the current upon the concrete.

THE results of a preliminary test made in 1911 on the effect produced by an electric current on the compressive strength of cement and concrete were included in a paper on "Electrolysis in Reinforced Concrete."* As stated in that paper, the experiments were of too short duration, thirty days, to make the results conclusive. In order to secure more evidence a new series was begun in September, 1912. The method used was essentially the same as in the preliminary series. A better means for keeping the cubes moist was devised; also, by tightly wrapping the cubes with rubber and friction tape, practically all the leakage was eliminated, so that all of the current in each circuit passed through the four cubes in series.

Unless exception is noted the following conditions will apply:

(1) The cement used was of the "Washington" brand, manufactured at Concrete, Washington. This brand is of good commercial quality, and is used extensively in the Puget Sound region. The tensile strength complies with the specifications for Standard Portland cement, as given by the American Society

*A. I. E. E. TRANS. Vol. XXX, p. 2055.

for Testing Materials. Chemical analysis and physical test data for this cement are given in Table 1.

TABLE I

Chemical analysis and physical test of the cement.

SiO_2	21	per cent
Al_2O_3	7	per cent
Fe_2O_3	2	per cent
CaO	66.5	per cent
MgO	1	per cent
SO_4	0.5	per cent
Na_2O and K_2O	2	per cent
Specific gravity		3.12

Fineness:—

Weight of sample		50.0 gr.	
Aver. of 3 samples	retained on 200 mesh	7.9 gr.,	14 per cent
	" " 100 "	0.29 "	0.58 per cent
	" " 50 "	0.02 "	0.04 per cent
Normal consistency 400 gr. cement 88 gr. water		21.6 per cent	
Penetration		10.5	

Tensile Strength:—

Aver. of 3 samples	24 hours	108 lb.
	7 days	499 "
	28 days	717 "

(2) The "fresh water" used was from Cedar River; the data from a chemical analysis and specific resistance are given in Table II.

TABLE II

Chemical analysis of Cedar River water expressed in milligrams per liter.

Nitrics	0.0
Nitrates	0.0
Free ammonia—a trace	
Albumenoid ammonia	0.0
Free oxygen	0.8
Chlorine	3.5
Total solid	41.0
Fixed solid	21.0

	at 20 deg. cent.	at 30 deg. cent.
Electrical conductivity per cm^3		
Cedar River water	20,100 ohms	15,600 ohms.
Fifth normal NaCl solution	54.4 "	45.4 ".

(3) The "salt water" used was a 3 per cent NaCl solution in Cedar River water.

(4) Natural sand, screened to pass a sieve having 20 meshes per linear inch and retained on a sieve having 30 meshes, was used.

(5) The gravel was screened to pass a sieve having 4 meshes per linear inch, and retained on a sieve having 8 meshes.

Two hundred and forty 2-inch (5-cm.) cubes were made as follows:

(a) Sixty cubes of cement with "fresh water."

(b) Thirty-six cubes of mortar with "fresh water."

Ratio of cement to sand, 1: 3.

[MAGNUSSON AND IZHUROFF]

FIG. 1—ARRANGEMENT OF TEST APPARATUS

(c) Twenty-four cubes of concrete with "fresh water."
Ratio of cement: sand: gravel = 1:1:1
(d) Sixty cubes of cement in "salt water."
(e) Sixty cubes of concrete in "salt water."
Ratio of cement: sand: gravel = 1:1:1

The cubes were made in accord with the specifications of the Committee on Uniform Testing of Cement, American Society of Civil Engineers.

Six bronze molds were used and six cubes were made at a time, and in the tables this is termed a "set." In making the cubes due care was taken to secure uniform conditions. The consistency was adjusted to give a reading of ten on the scale of a Vicat needle. The cubes were kept in the molds, under cover of a damp cloth to keep the air moist, for 24 to 28 hours.

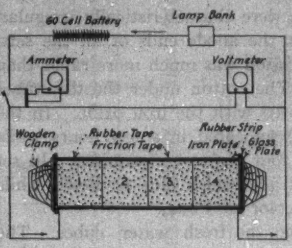

FIG. 2

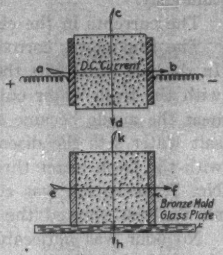

FIG. 3

At removal from the molds each was numbered, and then immersed in water, "fresh" for groups (a), and (b), and (c), and "salt" for (d) and (e), where they were kept for forty to sixty days, as recorded in Tables VII to X.

Four cubes from each set were then placed in the electric circuit; No. 1 nearest the anode, next No. 2 and No. 3, with No. 4 nearest the cathode. The remaining two cubes, No. 5 and No. 6, were kept in the water as control. As the four cubes in the electric circuit were kept moist throughout the experiment, the only factor affecting cubes No. 1-4 more than No. 5-6 would be the electric current passing through the former.

The arrangement of the cubes and the wiring is shown in Fig. 2. At each end an iron plate was placed, extending a little beyond the surface of the cubes, and having a copper wire soldered to one edge for electrical connection. A glass plate

and a rubber strip were placed outside the iron for insulation and the whole secured by a wooden clamp. By means of this clamp, pressure could be applied so as to give a fairly good contact between the iron plates and the cubes, and also to bring the four cubes into close contact. The sets were wrapped tightly with rubber tape, and this secured by friction tape. In order to keep the cubes moist small openings were made through the tape on top of the cubes. These openings were covered by inverted test tubes, full of water, salt or fresh, according to which had been used in making the cubes. See Fig. 1. Absorbent cotton was placed under the test tubes and in this way the water could slowly seep through the cotton and keep the cubes moist. A storage battery of 60 cells in series with a lamp bank was connected to the iron plates. The voltage was applied continuously.

The currents in the circuits were characteristically irregular.

The iron plates corroded at the anode ends of all the sets. In the salt water sets the corrosion was much more rapid than with the fresh water cubes. The cotton under the test tubes near the anode became saturated with the iron oxide. In the salt water sets the discoloring appeared in a few hours, while with the fresh water three or four days were required. In set No. 7 the cotton was colored a greenish blue or Fe_3O_4 while all the rest showed the red color of Fe_2O_3.

No odor was noticeable from the fresh water cubes. The chemical reactions probably consist simply of a decomposition of water and the formation of iron oxide.

$$3H_2O \longrightarrow 6\,H + 3O$$
$$3O + 2\,Fe \longrightarrow Fe_2O_3$$

No tests were made to determine a possible migration of sulphates and other salts.

An odor of chlorine accompanied the reactions in the salt water sets. The following equations give the main reactions:

$$4\,NaCl \longrightarrow 4\,Na + 4\,Cl$$
$$4\,Cl + 2\,H_2O \longrightarrow 3\,H\,Cl + H\,ClO + O$$
$$H\,Cl\,O \longrightarrow H\,Cl + O$$
$$2\,Fe + 3O \longrightarrow Fe_2\,O_3$$
$$Fe_2O_3 + 6\,H\,Cl \longrightarrow 2\,Fe\,Cl_3 + 3\,H_2O$$

The chlorine odor indicates the presence of hydrochloric acid and this may cause a secondary reaction that might affect the crushing strength of the cubes.

TABLE III

Compressive strength of cement cubes made in fresh water.

Cube Nos.		Direction of crushing	Compr. str. in pounds.	Compr. str. lb. per sq. in.	Compr. str. kg. per cm.²
	1	ab	48,580	12,145	851
	2	ab	47,380	11,845	832
	3	ab	38,950	9,737	684
Set No. 1	4	ab	49,000	12,250	860
	5	kh	42,720	10,680	750
	6	kh	53,570	13,392	940
	1	cd	43,040	10,760	756
	2	cd	46,980	11,745	824
	3	cd	43,630	10,907	765
Set No. 2	4	cd	40,160	10,040	704
	5	ef	36,650	9,163	644
	6	ef	50,770	12,693	890
	1	ab	35,720	8,930	626
	2	ab	39,870	9,967	700
	3	ab	35,220	8,805	618
Set No. 3	4	ab	35,020	8,755	615
	5	kh	40,650	10,162	713
	6	kh	31,840	7,960	559
	1	cd	30,530	7,630	535
	2	cd	38,190	9,548	670
	3	cd	29,290	7,323	514
Set No. 4	4	cd	35,430	8,857	622
	5	ef	29,350	7,337	515
	6	ef	24,730	6,183	434
	1	ab	35,250	8,812	619
	2	ab	40,240	10,060	706
	3	ab	30,700	7,675	539
Set No. 5	4	ab	34,630	8,657	607
	5	kh	38,000	9,500	667
	6	kh	28,730	7,183	503
	1	cd	31,740	7,935	556
	2	cd	39,350	9,837	690
	3	cd	43,550	10,888	765
Set No. 6	4	cd	40,340	10,085	707
	5	ef	30,470	7,618	535
	6	ef	45,560	11,390	800
	1	ab	41,760	10,440	734
	2	ab	35,140	8,785	616
	3	ab	36,030	9,008	633
Set No. 7	4	ab	44,290	11,072	778
	5	kh	40,000	10,000	702
	6	kh	29,750	7,438	522
	1	cd	45,770	11,443	801
	2	cd	35,520	8,880	623
	3	cd	38,640	9,660	678
Set No. 8	4	cd	34,510	8,627	605
	5	ef	40,050	10,012	704
	6	ef	46,380	11,595	813
	1	ab	41,660	10,415	730
	2	ab	42,920	10,730	752
	3	ab	41,355	10,339	725
Set No. 9	4	ab	44,440	11,110	779
	5	ab	47,050	11,762	827
	6	ab	42,140	10,535	740
	1	cd	32,800	8,200	576
	2	cd	40,480	10,120	710
	3	cd	43,775	10,944	768
Set No. 10	4	cd	42,450	10,612	744
	5	ef	39,160	9,790	687
	6	ef	40,760	10,190	715

TABLE IV

Compressive strength of concrete cubes in fresh water.

Cube Nos.	Direction of crushing	Compr. str. in pounds.	Compr. str. lb. per sq. in.	Compr. str. kg. per cm.²
1	ab	5,470	1,363	96
2	ab	5,430	1,358	95
3	ab	5,780	1,445	102
Set No. 11 4	ab	4,000	1,000	70
5	kh	5,090	1,273	89
6	kh	7,340	1,835	129
1	cd	6,800	1,700	119
2	cd	6,685	1,671	117
3	cd	6,800	1,700	119
Set No. 12 4	cd	7,820	1,955	137
5	ef	6,260	1,565	110
6	ef	8,000	2,000	141
1	ab	6,360	1,590	112
2	ab	9,120	2,280	160
3	ab	9,290	2,323	163
Set No. 13 4	ab	10,390	2,592	183
5	kh	10,100	2,525	178
6	kh	7,810	1,952	137
1	cd	8,980	2,245	158
2	cd	10,000	2,500	176
3	cd	10,830	2,707	190
Set No. 14 4	cd	11,760	2,940	206
5	ef	8,010	2,003	141
6	ef	11,000	2,750	193
1	ab	5,500	1,375	97
2	ab	5,750	1,437	101
3	ab	5,670	1,418	99
Set No. 15 4	ab	7,740	1,935	136
5	ab	5,590	1,398	98
6	ab	6,000	1,500	105
1	cd	13,480	3,370	237
2	cd	8,900	2,225	156
3	cd	12,210	3,042	214
Set No. 16 4	cd	8,970	2,243	158
5	ef	10,680	2,670	188
6	ef	11,570	2,892	203
1	ab	14,300	3,575	251
2	ab	12,220	3,055	215
3	ab	11,840	2,960	208
Set No. 17 4	ab	10,810	2,703	190
5	kh	12,390	3,098	217
6	kh	10,530	2,632	185
1	cd	14,470	3,618	254
2	cd	18,650	4,662	328
3	cd	17,380	4,345	305
Set No. 18 4	cd	16,740	4,185	294
5	ef	14,080	3,520	247
6	ef	12,250	3,063	215
1	ab	12,900	3,225	226
2	ab	19,590	4,897	344
3	ab	19,860	4,965	349
Set No. 19 4	ab	19,470	4,868	342
5	ab	16,230	4,058	286
6	kh	19,760	4,940	347
1	cd	12,370	3,092	217
2	cd	14,230	3,557	250
3	cd	9,850	2,463	173
Set No. 20 4	cd	12,980	3,245	228
5	ef	13,860	3,465	243
6	ef	13,170	2,292	231

Testing Cubes

Finally, the cubes in the electric circuit and the controlling cubes were tested for their compressive strength, using a Riehle 60,000-lb. testing machine. All cubes were tested under as nearly identical conditions as possible, using the same machine and at the same speed. In Tables III to VI inclusive are recorded the crushing strength of all the cubes tested. Numbers 1, 2, 3, 4 in each case have been in the electric circuit. One-half of the tested cubes were crushed in the direction of the flow of the current, and the other half were tested in direction perpendicular to the flow of the current. One-half of the control cubes were crushed in the direction of the open ends of the bronze mold and the other half in the direction of the sides of the mold. In Fig. 3 and in Tables III to VI, the corresponding directions with letters are given. In Tables VII to X inclusive are given the data for each set.

Summary

(a) The compressive strength of fresh water cement cubes was not affected by an average current density of 1.2 milliamperes per square inch (0.17 milliampere per cm^2) applied for 310 days. Tables III and VII.

(b) The compressive strength of fresh water concrete cubes was not affected by an average current density of 1.8 milliamperes per square inch (0.26 milliampere per cm^2) applied for 225 days. Tables IV and VIII.

(c) The compressive strength of salt water cement cubes was probably not affected by an average current density of 10.2 milliamperes per square inch (1.4 milliampere per cm^2) applied for 113 days. Tables V and IX.

(d) The compressive strength of salt water concrete cubes was not affected by an average current density of 13.8 milliamperes per square inch (1.9 milliampere per cm^2) applied for 110 days. Tables VI and X.

For (a), (b), (d) the average values for the cubes treated with the electric current were 1, 2, 3.0 and 2.5 per cent respectively, stronger than the corresponding control cubes. For group (c) the cubes in the electric circuit were 14 per cent weaker than the control. An examination of the crushing strengths in Table V will show that the apparent decrease is most likely due to a chance selection of too many of the stronger cubes for the control. If any action were due to the current the liberated

TABLE V

Compressive strength of cement cubes made in salt water.

Cube Nos.	Direction of crushing	Compr. str. in pounds.	Compr. str. lb. per sq. in.	Compr. str. kg. per cm.²
1	ef	34,400	8,600	604
2	ef	33,845	8,461	595
3	ef	31,900	7,975	561
Set No. 21 4	ef	27,140	6,785	475
5	ef	39,305	9,828	690
6	ef	40,510	10,128	712
1	kh	19,570	4,893	344
2	kh	30,610	7,652	537
3	kh	39,355	9,839	690
Set No. 22 4	kh	27,375	6,844	480
5	kh	39,540	9,885	694
6	kh	38,710	9,678	679
1	ab	18,895	4,723	332
2	ab	27,195	6,799	476
3	cd	35,790	8,947	627
Set No. 23 4	ab	28 500	7,125	500
5	ef	34,520	8,630	605
6	ef	36,450	9,113	640
1	cd	35,455	8,864	622
2	ab	22,440	5,610	394
3	ab	31,970	7,992	560
Set No. 24 4	ab	24,880	6,220	437
5	ef	37,800	9,450	664
6	ef	32,400	8,100	568
1	bd	27,890	6,973	490
2	ab	29,925	7,324	514
3	ab	24,510	6,127	430
Set No. 25 4	ab	20,570	5,142	361
5	ef	41,270	10,318	724
6	ef	31,720	7,930	555
1	cd	36,385	9,096	637
2	cd	34,480	8,620	605
3	cd	33,270	8,318	584
Set No. 26 4	cd	31,580	7,895	554
5	kh	37,190	9,297	652
6	kh	31,330	7,833	550
1	cd	38,328	9,580	673
2	cd	34,300	8,575	602
3	cd	33,325	8,331	585
Set No. 27 4	cd	33,390	8,348	586
5	ef	36,525	9,131	640
6	ef	28,250	7,063	496
1	cd	28,160	7,040	493
2	ab	22,240	5,560	390
3	ab	20,550	5,138	360
Set No. 28 4	ab	31,920	7,980	560
5	ef	36,900	9,225	647
6	ef	33,780	8,445	592
1	cd	42,190	10,548	740
2	cd	35,180	8,795	617
3	cd	35,720	8,930	626
Set No. 29 4	cd	40,775	10,194	715
5	ef	35,860	8,965	630
6	ef	33,220	8,305	582
1	ab	25,920	6,480	455
2	ab	25,360	6,340	445
3	ab	38,030	9,508	667
Set No. 30 4	ab	37,470	9,367	657
5	kh	36,730	9,183	644
6	kh	33,355	8,339	585

TABLE VI

Compressive strength of concrete cubes made in salt water.

Cube Nos.		Direction of crushing	Compr. str. in pounds.	Compr. str. lb. per sq. in.	Compr. str. kg. per cm.²
Set No. 31	1	ab	14,230	3,558	250
	2	ab	18,685	4,671	328
	3	ab	24,110	6,027	423
	4	ab	18,675	4,669	328
	5	ef	12,740	3,185	224
	6	ef	20,940	5,235	367
Set No. 32	1	cd	21,550	5,387	378
	2	cd	20,810	5,202	365
	3	cd	16,210	4,052	285
	4	cd	18,870	4,718	331
	5	ef	18,630	4,657	327
	6	ef	21,280	5,320	374
Set No. 33	1	ab	15,540	3,885	273
	2	ab	22,200	5,550	390
	3	ab	20,230	5,056	355
	4	ab	21,340	5,335	374
	5	kh	18,100	4,525	318
	6	kh	22,620	5,655	397
Set No. 34	1	cd	13,385	3,346	235
	2	cd	14,185	3,546	249
	3	cd	14,880	3,720	261
	4	cd	15,930	3,982	280
	5	kh	12,550	3,138	220
	6	kh	14,200	3,550	249
Set No. 35	1	ab	16,220	4,055	285
	2	ab	23,275	5,819	408
	3	ab	25,330	6,332	445
	4	ab	22,380	5,595	393
	5	ef	17,380	4,345	305
	6	ef	21,330	5,332	374
Set No. 36	1	cd	23,325	5,831	410
	2	cd	19,120	4,780	336
	3	cd	19,780	4,945	347
	4	cd	26,690	6,672	468
	5	ef	23,720	5,930	416
	6	ef	24,500	6,125	430
Set No. 37	1	cd	21,900	5,475	384
	2	cd	18,140	4,535	319
	3	cd	18,920	4,730	332
	4	cd	16,120	4,030	283
	5	kh	16,140	4,035	284
	6	kh	18,200	4,550	320
Set No. 38	1	ab	15,565	3,891	273
	2	ab	13,625	3,406	239
	3	ab	11,545	2,886	203
	4	ab	12,370	3,092	217
	5	ef	14,260	3,565	250
	6	ef	13,270	3,318	233
Set No. 39	1	cd	18,170	4,542	319
	2	cd	15,190	3,797	267
	3	cd	17,000	4,250	299
	4	cd	15,670	3,917	275
	5	kh	18,200	4,550	320
	6	kh	14,070	3,518	247
Set No. 40	1	cd	11,030	2,757	193
	2	cd	14,745	3,686	259
	3	cd	15,000	3,750	263
	4	cd	13,630	3,407	240
	5	kh	14,020	3,505	246
	6	kh	13,220	3,305	232

TABLE VII

Average compressive strength of cement cubes made in fresh water.

No. set.	Total days	Hrs. in electric circuit	Aver. volts	Total amp. hours	Av. comp. str. lb. per sq. in. test cubes	Av. compr. str. kg. cm.^{2} test cubes	Av. compr. str. lbs. per sq. in. control cubes	Av. compr. str. kg. cm.^{2} cont. cubes	% change in compressive strength
1	435	7500	116	35	11494	807	12036	845	— 4.5
2	398	7476	116	35	10863	762	10928	767	— 0.2
3	397	7452	116	35	9114	640	9061	636	+ 0.6
4	370	7452	116	35	8339	585	6760	475	+18.7
5	366	7443	116	34	8801	618	8342	585	+ 5.5
6	361	7443	116	34	9686	680	9504	667	+ 1.9
7	360	7442	116	34	9826	690	8719	612	+11.7
8	359	7441	116	34	9652	677	10804	758	—11.2
9	349	7277	116	34	10648	747	11148	784	— 4.5
10	345	7276	116	34	9969	700	9990	701	— 0.2
				Average	9840	691	9729	683	+ 1.2

TABLE VIII

Average compressive strength of concrete cubes made in fresh water.

11	344	7075	116	45	1292	91	1554	109	—16.8
12	339	7074	116	45	1756	123	1783	125	— 1.5
13	311	5245	116	36	2196	155	2238	157	— 1.9
14	305	5245	116	36	2598	182	2375	166	+ 9.4
15	302	5244	116	36	1541	108	1449	101	+ 6.2
16	301	5243	116	36	2720	191	2781	195	— 2.2
17	299	5225	116	36	3073	216	2865	201	+ 7.2
18	297	5224	116	36	4202	295	3292	231	+ 2.8
19	296	5223	116	36	4488	316	4499	316	— 0.2
20	295	5222	116	36	3089	217	3378	237	— 8.5
				Average	2695	190	2621	184	+ 3.0

TABLE IX

Average compressive strength of cement cubes made in salt water.

No. set.	Total days.	Hrs. in elec. circuit.	Average volts.	Total amp. hours	Av. comp. str. lb. per sq. in. test cubes	Av. compr. str. kg. per cm.^{2} test cubes	Av. compr. str. lb. per sq. in. control cubes	Av. compr. str. kg. per cm.^{2} contr. cubes	% change in compressive strength
21	439	2744	101	80	7955	559	9977	701	—20.2
22	438	2833	91	128	7307	513	9781	687	—25.3
23	435	2760	98	155	6898	484	8872	622	—22.3
24	433	2820	97	132	7172	503	8775	616	—18.5
25	419	2649	92	122	6391	449	9124	640	—29.9
26	418	2703	92	105	8482	595	8565	601	— 1.0
27	414	2711	95	94	8708	612	8097	568	+10.7
28	415	2688	93	99	6429	451	8835	620	—27.2
29	412	2643	91	97	9617	675	8635	606	+11.4
30	411	2639	95	88	7924	556	8761	615	— 9.5
				Average	7689	540	8943	628	—14.0

TABLE X

Average compressive strength of concrete cubes in salt water.

31	412	2663	91	148	4731	332	4210	296	+12.4
32	409	2 64	91	139	4840	340	4899	350	— 2.8
33	403	2665	94	145	4957	348	5090	357	— 2.6
34	403	2642	91	143	3648	256	3344	235	+ 9.1
35	402	2666	94	155	5450	383	4838	340	+12.0
36	401	2667	96	146	5557	390	6027	423	— 7.8
37	401	2642	92	145	4692	329	4293	302	+ 9.3
38	400	2639	91	150	3319	233	3441	242	— 3.5
39	398	2674	93	142	4127	290	4034	283	+ 2.3
40	397	2651	91	149	3400	239	3405	239	0.0
				Average	4472	314	4367	306	+ 2.5

chlorine would be the most likely agent. Since the chlorine is liberated at the positive pole, it would appear at cube No. 1. In sets No. 22 and No. 23, the cube No. 1 was weakest, but in sets No. 27 and No. 29, cube No. 1 was strongest. Moreover, cube No. 1 in set No. 29 was the strongest in the whole series and hence not likely to have been weakened by the current. The series shows less uniformity in strength than the cubes in either (a), (b) or (c).

Averaging the averages for the four groups, the strength of the cubes Nos. 1, 2, 3 and 4 was only 1.8 per cent less than the control cubes Nos. 5 and 6; and this difference is well within the errors of the experiment.

Summarizing the results, we find that for *the current density covered by the experiments* the current produces no change in the compressive strength of the cubes. This is in accord with the preliminary observations in the earlier paper (A.I.E.E. TRANS. XXX, p. 2967).

Within the limits of current density for which these conclusions apply, it follows that failures in reinforced concrete due to electrolysis are due entirely to the forces produced by increase in volume when the iron is changed into iron oxide, and not by any direct action of the electric current upon the strength of the concrete.

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EXPERIENCES WITH LINE TRANSFORMERS

BY D. W. ROPER

ABSTRACT OF PAPER

This paper presents an analysis of the transformer troubles for one year on a system having nearly 15,000 transformers installed. This analysis indicates that about 50 per cent of the troubles traceable to the transformer can be eliminated, with no great expense, by some slight changes in the construction details and some improvements in operating methods.

Reference is made to the Standard Specifications for Line Transformers issued by the Bureau of Standards. An experiment on 1600 transformers with the connection board removed or submerged proved that the connection board above oil was responsible for about 60 per cent of the transformer troubles due to lightning. Curves showing the record of burn-outs of four different makes of transformers are used as a basis for a discussion of the effect of the value placed on continuous service in the selection of transformers.

The results of experiment with improved lightning protection are given, showing how the troubles were reduced by two-thirds. By taking advantage of the results of the two extended experiments, it should be possible to reduce the troubles due to lightning to about 10 per cent or 20 per cent of the troubles heretofore experienced.

WITHIN recent years the line transformer has been developed by the manufacturers into one of the most efficient and reliable pieces of electrical apparatus. It is fortunate for the central station industry that this is the case, as the distributing transformer, next to the meter, is the piece of apparatus nearest to the customer and for that reason its shortcomings would be most readily noticed. While the breakdowns of apparatus or transmission lines in general involve only a very brief interruption to the service, if any, the failure of a transformer generally means an interruption of several hours and especially so if it is located in a sparsely settled region where inter-connection of secondaries is not possible.

That the transformer is a reliable piece of apparatus is evidenced by the fact that last year the total cost of maintenance and repairs of all transformers, on the distributing system with

which the author is connected, was about 2 per cent of the value of all transformers at present prices. This figure indicates that any suggestions for improvements would be in the nature of refinements in design or construction, and further, that if such refinements involve any material increase in the price they would be justified only for those companies which place a high value on continuous service to their customers. It appears possible, however, by some slight changes in the details of construction of the transformer and some improvements in operating methods, and without any material additional expense, to eliminate about 50 per cent of the troubles directly traceable to the transformer.

After witnessing the laboratory tests to which the modern transformer can be subjected without injury and after noting the excellent results of the tests for copper loss, iron loss and regulation, it is difficult to state just how further improvements in the transformers might be made. If, however, an operating company having approximately 15,000 line transformers in service adopts continuous service as a bogey score and keeps a careful record of the troubles experienced with the transformers in service, the lines to be followed in making further improvements in the quality of transformers and in their details of construction become somewhat more apparent. A record for the year 1913 of the transformer troubles on the system familiar to the writer is given in Tables I and II.

In discussing possible improvements in the specifications of transformers, it is convenient to use as a basis the standard specifications for transformers issued by the Bureau of Standards as Circular No. 22 in 1911. The introductory paragraph in these specifications reads as follows:

> These specifications have been drawn up with the purpose of providing a standard specification for the purchase of transformers of the type most commonly used both by the government departments and by other purchasers. They have been so drawn as to secure the most serviceable apparatus on the market, and at the same time to admit the regular product of reputable manufacturers. To this end the coöperation of government engineers and of representatives of many of the leading manufacturers has been secured, and it is largely due to help and criticism from these sources that the specifications are representative of the best practise among manufacturers.

It is assumed that these specifications fairly represent the present American practise. The criticisms of the specifications which follow are, therefore, to be considered as being directed against the present practise rather than against the specifications.

TABLE I

RECORD OF TRANSFORMER TROUBLES FOR THE YEAR 1913.

Size of transformers	Cause of Troubles						Total transformers in service Dec. 31, 1913
	Lightning.	Overloads	Defective.	Grounds and short circuits on secondary wiring	Miscellaneous and unknown	Totals	
	Number of cases of trouble.						
1	4	–	2	–	2	8	444
1.5	26	2	4	2	12	46	1,108
2	16	2	1	3	6	28	1,100
2.5and3	21	3	3	2	3	32	2,235
4	13	2	4	–	2	21	1,056
5	9	–	4	1	6	20	1,951
7.5	23	–	2	–	11	36	2,071
10	9	–	2	1	1	13	1,626
15	2	1	–	–	–	3	1,113
20	1	–	–	–	–	1	515
25	1	–	–	–	–	1	350
30	1	–	–	–	–	1	207
37.5and40	–	1	–	–	1	2	139
50	2	1	1	–	1	5	241
75	–	–	–	–	–	0	43
100	1	–	–	–	2	3	54
150	–	–	–	–	–	0	3
200	–	–	–	–	–	0	16
250	–	–	–	–	–	0	2
Totals,	129	12	23	9	47	220	14,274

Total capacity, 129,056 kw.

Approximate total value at present prices, $1,000,000

TABLE II

RECORD OF THE FUSES BLOWN AND CUT-OUTS DESTROYED DURING THE YEAR 1913.

	Due to Lightning	Other Causes	Total
Fuses blown	911	678	1,589
Transformers burned out	129	91	220
Total cases of trouble	1,040	769	1,809
Cut-outs destroyed	77	332	409
Ratio of cut-outs destroyed to total cases of trouble	7.4	43.	22.5

The experiences of the author on which this paper is based have been gathered during his connection with the system of the Commonwealth Edison Company in Chicago, and it will be understood, unless otherwise specified, that the experiences and records herein mentioned refer to the system of this company. As this distribution system covers about 125 square miles of territory, including sparsely settled suburban districts, as well as thickly settled urban territory, it is thought that the installation may be regarded as fairly typical.

Name Plate

The standard specifications require a name plate, but make no mention as to its location. It is the custom of the manufacturers to furnish a name plate on which the lettering is of sufficient size to be read when the transformer is standing on the storeroom floor, but which is somewhat more difficult to read when the transformer is installed on the pole. Securing the correct number of a transformer is made particularly difficult in the larger sizes of transformers because the name plate is located on the front of the case near the top. This puts the name plate so far from the pole that the lineman must unsnap his life belt in order to get in a position where he can read the name plate. If the *safety first* campaign is to be extended to name plates on transformers, they will be located in such a position and the lettering will be of such a size that a lineman, without risking his life, can read the name plate while the transformer is in position on a pole.

Cases

The standard specifications provide for eyebolts or hooks for handling transformers. The transformers, however, must be handled many times while in the storeroom or in transit from the storeroom to the line. Last year, in Chicago, the number of transformers replaced in order to increase the capacity was equal to the number installed, and the total number handled during the year was over 40 per cent of the number on the lines at the end of the year. Transformers of 5 kw. and smaller capacity comprise over 60 per cent of the total number installed. With the class of help that is used in this work it is very difficult to prevent the men from using the primary or secondary leads as handles. It appears possible for the manufacturers, at no great expense, to fashion the covers of the

smaller sizes of transformers so as to provide a handle on each side that would be somewhat more convenient for the purpose than the primary leads.

No mention is made of terminals on the primary or secondary leads, but such terminals appear to be quite desirable and are furnished by some manufacturers. It has been suggested that terminals should be located just outside of the porcelain bushings with a solid rod through the bushing. If this could be done, the leads would be so short that there would be no temptation to use them as a handle and, in addition, the solid rod sealed into the bushings would absolutely prevent the siphoning of the oil through the leads. In this manner two of the most aggravating petty annoyances in connection with transformers would be eliminated.

Cut-Outs

The specifications require two primary cut-outs to be furnished with each transformer, but make no mention as to the qualities desired in these cut-outs, assuming apparently that any cut-outs supplied by the manufacturer will be satisfactory. This assumption is not warranted by experience. The number of cut-outs replaced in a year exceeds the total number of burned-out transformers, indicating that the cut-outs are a less reliable piece of apparatus than the transformers. On the system under discussion the larger sizes of transformers were operated without cut-outs for several years, as it was found that better service could be given to customers in this manner than with the types of cut-outs which were available.

If a company is buying transformers on specifications, the probabilities are that within a few years there will be transformers on hand made by several manufacturers, and as several makers furnish their own type of primary cut-out with the transformers, the operating company will soon have several types of cut-outs and must keep in stock and furnish to their troublemen a full line of the various sizes of primary fuses for each of the several makes of transformers. It would be a better plan to have the transformer furnished without cut-outs and for the operating company to secure the cut-outs that are found to be best adapted to its purpose, using one type for the smaller sizes, with one or two additional types of cut-outs for the larger sizes of transformers. Enclosed fuses appear to be the only satisfactory type for the sizes above 40 kw. Some of the points that should be included in the specifications for transformer cut-outs are as follows:

(1) They should be capable of opening the circuit of the transformer whether the short circuit occurs when the cut-out is cold or when it is heated, due to the load.

(2) It should be impossible for the plug to drop out due to the jarring of the pole, or to be blown out by blowing of the fuse or by short circuits or arcing in the cut-out.

(3) It should have sufficient distance between terminals so that if the fuse blows in a driving rain or wet snow storm, the current will not leak across the cut-out between terminals and destroy the cut-out.

(4) The plug should be provided with a handle of such size and shape that the cut-out can be readily removed by a troubleman when wearing rubber gloves and when the handle is wet with rain or covered with sleet.

(5) The plug should have a shield of such size and shape that when the plug is inserted on a short-circuited transformer the resulting arc will not cause any injury to the troubleman.

(6) The cut-outs for the smaller sizes of transformer should be designed for the use of metal strip fuses. The fuse-holding parts should be designed so that the fuse can be readily replaced.

Some further attention should also be given to the subject of the metal strip fuses for primary cut-outs. In some parts of the city these fuses corrode badly, reducing the cross-section of the strip so that the fuses will blow on light loads, and without any apparent trouble in the transformer or on the customer's premises. Some experiments are being made with coated fuses which it is hoped may eliminate this trouble.

Connection Boards

The specifications require that: "The ends of the primary coils shall be brought to a convenient connection board of porcelain or other suitable material within the case and so arranged that the primary coils may be put in series or in multiple", and also that: "Sufficient oil shall be furnished to completely immerse core, windings, and connection board."

All of the manufacturers do not agree that the terminal board should be submerged. It has even been contended that the connection board could be so designed and located that the lightning would jump across the terminals of the primary coils or from the primary terminals to the cover before the potential across the terminals of the coils could rise sufficiently high to burn out the coils. In looking for evidence bearing on

this theory it was found that the repair shops had been, for several years, removing the connection boards from all transformers that were re-wound, and that the percentage of troubles on these transformers was less than with new transformers containing connection boards. An investigation was made of all the transformers whose fuses had blown during a severe lightning storm, and signs of arcing at the terminal board were found in a large percentage of the transformers. These facts seemed to indicate that the connection board was the cause of many of the troubles during lightning storms. For the purpose of checking this theory one circuit with a total of about 250 transformers was equipped with transformers having the con-

TABLE III

COMPARATIVE RECORD OF TRANSFORMER TROUBLES DUE TO LIGHTNING, WITH TRANSFORMERS HAVING CONNECTION BOARDS ABOVE OIL AND WITH CONNECTION BOARDS REMOVED OR SUBMERGED.

		Location of connection boards.	
		Above oil.	Removed or submerged.
1. Number of transformers		9,878	1,648
2. Fuses blown without damage to transformers	Number	770	56
	Per cent	7.8	3.4
3. Coils burned out	Number	77	10
	Percent	0.78	0.61
4. Connection boards damaged, leads burned off, etc.	Number	36	0
	Per cent	0.36	0
5. Total classed as burn-outs, sum of items 3 and 4	Number	113	10
	Per cent	1.14	0.61
6. Total cases of trouble, sum of items 2,3 and 4	Number	883	66
	Per cent	8.95	4.01

nection boards removed or submerged. Careful records were kept during the succeeding year, but the results were disappointing, due apparently to the small number of transformers involved in the experiment. Before the following lightning season arrived, additional circuits were provided with transformers having the connection boards removed or submerged, so that the total number exceeded 1600 transformers. The scheme of lightning protection was not changed, so that the only difference between these transformers and those conforming to standard practise was the removal or submerging of the terminal boards. The results of this experiment for the year 1913 are shown in Table III. In this table, under the heading

"fuses blown" are included all cases of trouble which involved blowing of the primary fuse but which left the transformer in operating condition. Under "burn-outs" are included all transformers which were not in condition for service and had to be replaced. The results as shown in this table indicate that the terminal board above oil is the cause of about 60 per cent of the troubles during lightning storms. The results further indicate that the connection board does not act as a lightning arrester in protecting the transformer coils from damage, but on the contrary that a larger percentage of coils is burned out when transformers are provided with such connection boards above oil than when they are removed or submerged.

It appears, therefore, that the standard specifications have taken a long step forward in specifying that the connection boards must be submerged under oil, but as only a small percentage of the transformers that are provided with connection boards are ever used on 1000-volt circuits, it is therefore suggested that a further improvement could be made by requiring that transformers for use on 2000-volt circuits shall be furnished without connection boards and limiting the use of transformers with submerged connection boards to those companies which have 1000-volt distributing circuits.

Oil

The standard specifications require that oil be furnished with the transformers. The situation with oil is somewhat similar to that regarding cut-outs. Each of the several manufacturers furnishes a different type of oil, so that with several makes of transformers in use it would be necessary to keep on hand several kinds of transformer oil and to see that the proper kind of oil was sent out with each transformer. It is possible to obtain a good grade of transformer oil which is entirely suitable for use with all of the several makes of transformers now on the market. Therefore, it appears to be a better practise in purchasing transformers on specifications, to require that they shall be furnished without oil, and to buy the oil separately under proper specifications, provided, however, that the purchaser has suitable facilities for making the necessary tests.

Design, Materials and Workmanship

The standard specifications contain a paragraph reading as follows: "Action upon these features will be based on the

requirements of the specifications and observations made while the apparatus is under test." Later in the specifications, under the head of "Basis for Comparing Guarantees", is a paragraph reading as follows:

> In case the proposals offered by different bidders in accordance with these specifications guarantee core losses less than those specified in Table I, each watt of difference shall be evaluated at $0.88 for purposes of comparison. For the same purpose, copper loss shall be evaluated at $0.33 per watt for each watt difference between values specified in Table I and the full-load value guaranteed by the bidder.

An inference that can be readily drawn from these two paragraphs is that having passed the qualifying specifications and having been subjected to a critical examination while the transformer was under test, the several transformers furnished by the various manufacturers are then to be considered of equal value except as to the copper and iron losses, and that the relative value of the transformers submitted by the different manufacturers can then be determined by the process of valuation above described. If this assumption was borne out by experience, then we would expect to find that the percentage of burn-outs of the various makes of transformers from all causes during the period of the year was approximately equal.

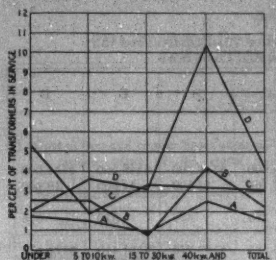

FIG. 1—RECORD FOR ONE YEAR OF TRANSFORMER BURN-OUTS FROM ALL CAUSES.

Each line represents a different make of transformer.

In Fig. 1 are shown the results of a recent year's experience with four different makes of transformers. All of the transformers included in these results have passed tests virtually identical with the qualifying specifications above referred to, but, as shown by the figure, there is a wide range in their ability to withstand the conditions of service. The percentage of burn-outs in service for the best transformer was about one-third of the percentage for the rest. It is, therefore, submitted that it should be possible to devise a specification so that there would not be so great a range in quality of the transformers which have passed the specifications.

In order that the cost of the transformer losses and the cost of repairs of the various types may be shown in their proper

relation to each other, the results shown in Fig. 1 have been applied to the entire installation, assuming that all of the transformers on the system are of each of the several types, and estimates made showing what the total cost of repairs for one year would have been for each of these types of transformers. The iron and copper loss guarantees were also obtained from the same four manufacturers and the total losses for one year were calculated on the assumption that all of the transformers were furnished by each of the several manufacturers. The results of these calculations with different values assumed for the losses and for continuity of service are shown in Tables IV and V. It is not intended that the assumed values should represent the opinion of the author as to the value of these items, but they

TABLE IV

OPERATING COSTS OF FOUR TYPES OF TRANSFORMERS FOR THE YEAR 1913, UNDER ASSUMED CONDITIONS

	A	B	C	D
1. Cost of iron and copper losses at an assumed value of 1.5 cents per kw-hr	$158,600	$148,300	$146,000	$154,000
2. Replacing and repairs	7,700	11,100	14,900	19,800
3. Estimated loss of income, due to burn-outs	265	370	510	675
4. Total of items 1, 2 and 3	$166,565	$159,770	$161,410	$174,475
5. Loss of prestige, (assumed as 15 times loss of income)	3,975	5,550	7,650	10,125
6. Totals of items 4 and 5	$170,540	$165,320	$169,060	$184,600

were assumed over a wide range for the purpose of showing the effect which these values would have in the selection of the best type of transformer for any particular set of conditions. An inspection of these tables shows that the determination by an operating company of the best transformer for its purposes depends upon the values placed by it on the transformer losses and on the continuity of service. If it places a high value on the transformer losses, this feature will determine the best transformer for its purposes. The figures also show that the cost of repairs is a comparatively minor item and that a high value must be placed on continuity of service in order that the savings due to the most reliable transformer may offset the cost of its increased losses.

The Protection of Transformers

Transformers while in service must be protected from overloads and from lightning. It is customary to endeavor to protect against overload by means of primary fuses. In practise, a great many minor troubles occur on the premises of customers which will blow the primary fuses. Such troubles should result in the blowing of the secondary fuses on the premises of the customer and the primary fuses should not blow unless there is trouble within the transformer. To secure this result, the transformer must have primary fuses corresponding to several times its rated capacity, so that a slowly increasing load would burn out the transformer. Protection from overloads is best

TABLE V

Operating costs of Four Types of Transformers for the Year 1913, under Assumed Conditions.

	A	B	C	D
1. Cost of iron and copper losses at an assumed value of 0.5 cents per kw-hr.	$52,860	$49,450	$48,600	$51,500
2. Replacing and repairs,	7,700	11,100	14,900	19,800
3. Estimated loss of income, due to burn-outs,	265	370	510	675
4. Totals of items 1, 2 and 3,	$60,825	$60,920	$64,100	$71,975
5. Loss of prestige, assumed as 15 times loss of income)	3,975	5,550	7,650	10,125
6. Totals of items 4 and 5,	$64,800	$66,470	$71,750	$82,100

secured by proper records and by occasional tests as a check on the records. During the year 1913, the number of transformers burned out by overload was less than one-tenth of one per cent of the number installed. This record indicates the entire feasibility of protecting transformers against overload by means of the records and tests. The primary fuse should therefore be regarded as a device for disconnecting a defective transformer so as to protect the rest of the service, and not for the protection of the transformer itself from overloads.

Protection of distributing transformers against lightning has apparently not received the attention that it deserves. The record of lightning troubles for the year 1913 is shown in Fig. 2. These results show that the larger sizes of trans-

formers are comparatively immune from lightning, and that the greatest number of troubles occur with the smaller sizes, that is, the sizes below 10 kw. The number of transformers of these sizes comprises about 70 per cent of the total installation, so that the transformers which are most susceptible to damage by lightning are the most numerous. It is suggested that careful attention by the manufacturers to the primary bushings, the clearance of the primary leads inside the case, the manner of their support and other minor details, would probably result in a material improvement in these records.

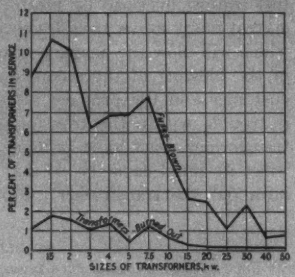

FIG. 2—RECORD FOR ONE YEAR OF TRANSFORMER TROUBLES DUE TO LIGHTNING.

In addition to the experiments mentioned above, which involved the removal of connection boards from a large number of transformers, some further experiments were made in another area, which consisted in

TABLE VI

RECORD OF TRANSFORMER TROUBLES DUE TO LIGHTNING, SHOWING THE IMPROVEMENT IN SERVICE DUE TO THE INCREASED LIGHTNING ARRESTER PROTECTION.

		Ratio of arresters to transformers	
		40 per cent	100 per cent
Location of arresters,		On line poles.	On transformer poles.
Number of transformers,		9,878	1,560
Fuses blown,	Number	770	85
	Per cent	7.8	5.5
Transformers burned out,	Number	113	6
	Per cent	1 .15	0 .39

NOTE: All transformers had connection boards above oil.

installing lightning arresters upon the same pole with each of a large number of transformers. The remainder of the distributing system in question is protected by arresters not located

on the transformer poles but scattered over the lines at a distance of about two thousand feet, resulting in a ratio of arresters to transformers of about 40 per cent. The results of these experiments are shown in Table VI.

In that portion of the territory where there was an arrester on the same pole with each transformer, the results to date as compared with the older practise indicate that the percentage of transformers burned out by lightning is reduced by about two-thirds. The several experiments indicate that by the combination of the two schemes and possibly by some further improvements in some details of the transformers and in the design of the lightning arresters, there should be no great difficulty in reducing the percentage of cases of trouble due to lightning to one-fifth, and possibly to one-tenth, of those experienced in former years. It is hoped that more definite and complete information on this subject may be available within another year.

DISCUSSION ON "EXPERIENCES WITH LINE TRANSFORMERS," (ROPER). PITTSFIELD, MASS., MAY 28, 1914.

W. S. Moody: I think that manufacturers and designers of transformers owe a great deal to Mr. Roper for the preparation of this excellent paper; not only because of the information that it contains as to experiences and opinions, but because it is a little unusual to give so fully the experience of the user of apparatus, to the manufacturer. However scientifically and carefully apparatus may be designed, there are, of necessity, a great many things that nothing but service will demonstrate, and the manufacturer cannot benefit by that experience in service to any great extent without the very complete assistance of the operating man, and that assistance is not always available. The operating man is rather inclined to look at these figures as his private property, and the manufacturer does not get the full benefit of them.

I think the operator is sometimes inclined to criticise the manufacturer for being slow in complying with the suggestions and criticisms of those who use his apparatus, but I do not think there is any danger of this criticism being justly applied when data as complete as Mr. Roper gives in his paper are available to guide a manufacturer in his decision as to whether a change is necessary or not.

The whole question of reliability of apparatus, and transformers in particular, is essentially one that needs just this co-operation between the manufacturer and the user. The manufacturer, if he wants to establish such a reputation as every manufacturer should seek to establish, naturally wants to make his apparatus just as reliable as possible, but, as Dr. Jackson has intimated, it is possible to spend money that is not justified in attempting to get extreme reliability, and consequently it is only by keeping very exact records as to reliability, that the point at which it is economical to have additional factors of safety can be determined; but I think there is, after all, not much danger of the reliability side of the question being overdone.

Cost, low weight, small size, high efficiency, and in fact every other desirable point, are diametrically opposed to the features that go to make up long life; consequently, there is little chance that either the manufacturer or the user will be over-concerned with reference to reliability.

A. D. Fishel: It has been stated by Mr. Roper that the distributing transformer naturally forms one of the most important links in a large distributing system; further, that it has been one of the most reliable links in that system. The distributing transformer has always been located in a portion of the system where it received comparatively little attention. However, we now come to a point where more attention is to be given to proper protection of such transformers, in addition

to the improvements in the transformers which have been effected during the past few years, and there is no doubt that the results should lead to more reliable service. It is important, of course, that the distributing transformer should be thoroughly weather-proof, as efficient in operation as possible and absolutely reliable from the standpoint of safety. In a large system, characteristics that become of special importance are those features that lead to continuity of service. There have been marked improvements in the design, construction and manufacture of distributing transformers during the past few years and each one of these three items has some effect in determining the life and the reliability of the transformer, as well as tending to provide continuity of service.

These improvements in the small-capacity distributing transformers were largely made during the time that the alloy sheet steels were being adopted. It was the endeavor, with that development, to obtain in the design of such transformers a balance of all of the many characteristics that are desirable for a distributing transformer, and these included the characteristics that tend to reliability and continuity of service.

The changes in design which accompanied this development, usually tended to increase the factors of safety in the design. In considering the desirability of some detail of design, all of the factors must be considered, because such a detail might not be suitable for one particular design only because it was not backed up with sufficient safety factors at other points or because of insufficient space to permit proper application, etc. This fact applies to the matter of the location of the transformer terminal board.

As I understand Mr. Roper's paper, most of the transformers referred to in Table III are not of the particular types or designs that are now available on the market. Therefore it is doubtful whether a safe conclusion concerning such a detail of design, as based on these data, can be reached with regard to present types of transformers. The modern transformer probably has greater factors of safety in the insulation, more uniform temperature rise and similar qualities that lead to a more reliable transformer and therefore it can be provided with a terminal board that will operate safely and to some advantage at the oil level. Thousands of transformers of such construction have been giving very satisfactory service.

Such transformers necessarily have greater clearances at the terminal boards and possess other differences in design. There was obtained the advantage of the terminal board providing a support to the leads about midway from where they issue from the coils to where they enter the outlet bushings. Another advantage was the absolute prevention of the siphoning of oil from the case, which Mr. Roper states is one of the petty annoyances met with in operation. In fact, I believe that there has not been a single complaint about siphoning of oil

under any reasonable operating conditions, out of tens of thousands of such transformers in service.

The location of the terminal board will depend largely upon the design of the transformer, the clearances available and the operating stresses which may have to be met. For distributing voltages considerably higher than the 2200-volt classes referred to in this paper, I do not believe that it would be advisable to have a connection board at the oil level. This, for example, would apply to 6600-volt, high-tension distributing transformers. With such transformers, the clearance distances, as well as the terminal board itself, would have to be too large, requiring much more space than is necessary to effectively apply the same on transformers of lower voltage.

After all, the most desirable development would be the elimination of a high-tension terminal board, and that brings up the question of voltage standardization. It is very desirable from many standpoints that voltages and taps should be standardized. On these small transformers, where continuity of service is to be a criterion, multiple voltages and extra taps should be eliminated wherever possible and one of the main functions of the terminal board will be automatically eliminated. It would therefore be very desirable to adopt single voltages on distributing transformers on the high-tension side, where, of course, such simplification is more important than on the low-tension or secondary side.

With a single high-tension voltage, the terminal board could most successfully be replaced with porcelain spacers approximately at the oil level, to provide the desirable support for the leads, without impeding the circulation of the oil, and keeping the high-tension spacer separate from the low-tension board, so that there would be less possibility of the lineman making a mistake in handling.

With regard to the handling of the transformers, some of those now available have lugs, for lifting, cast on the sides of the case and these lugs form a convenient method of pulling the transformers around the floor, so that the leads should not have to be used for this purpose. With some of the modern transformers, the connection to the weatherproof cable leads is made inside of the porcelain outlet bushings, so that it requires considerable mishandling of the leads to injure the transformer insulation, especially with the more substantial high-tension bushings which are now provided.

Considerable attention has also been given, during the past two or three years, to the fuse block question, and porcelain fuse blocks of the receptacle and plug type are now available which are much more reliable and embody most of the characteristics which Mr. Roper sets forth as an index to a good transformer primary cut-out.

I believe that Tables No. IV and V refer to electrical performance of the later types of transformers, while they are

considered in connection with the operating records of transformers of older designs and construction, which would not possess these electrical performances. Changes in the electrical performance may be accompanied by changes in construction that would considerably affect the operating record.

It would seem to be doubtful whether the reduced electrical stress on transformer insulation due to better protection would have any direct effect upon the life of the insulation. Fatigue of the insulation would only come if the stresses were of prolonged duration so that heat stresses would develop, while high-frequency or lightning disturbances are of relatively short duration.

There is no doubt that the better the protection against lightning disturbances, the more reliable will be the operation. There is considerable doubt, however, as to the number of such arresters which it would be practical to install in the average system. Each arrester means an additional link in the system which must be given a certain amount of attention to insure being in good operating condition. Further, the cost for obtaining grounds for each of these arresters would in many cases be higher than that in the city of Chicago, where grounds may probably be obtained at a fairly low cost. Of course, one must have a good ground to have an effective arrester.

It would be desirable to have an accelerated life test as an index of the reliability of the transformer, but it is going to be very difficult to determine on anything in the way of a reliable accelerated life test on a static transformer, such as may be obtained on moving apparatus, as the conditions are vastly different. Practically all that we can do is to study the service conditions, the material that goes into the transformer, see that it is put in in such a way that it will be permanent, that the insulation is properly reinforced, that the temperature rise is low and uniform and look into the various other details of design, construction and methods of manufacture that may affect the relative life of the transformer, but it is very hard to provide any single test as a real measure of such life.

H. W. Hough: As far as we have been able to find out in Cleveland, our experience checks up with Mr. Roper's statement regarding the Chicago conditions. We had approximately ten thousand transformers in service during the past year, and of that number about four hundred were brought in classed as burned out, whether from the coils being burned out or the leads or terminal boards being damaged. It was a fact that in the great majority of cases the terminal boards were damaged, whether the other effects were there or not. About ten per cent of our transformers have submerged terminal boards, and during the past year there has not been any case on record where the terminal board was damaged when it was submerged. I thought perhaps this statement would add a little to Mr. Roper's side of the question.

Paul M. Lincoln: If we take Mr. Roper's paper at its face value, he apparently has demonstrated that the submergence of the terminal of the connection board is a highly desirable thing in the distributing transformers such as he deals with. I would like to raise the question as to whether Mr. Roper has completely proved that point.

One of the points I want to call attention to is Table No. VI. In Table VI, I think Mr. Roper has shown beyond a question that if a lightning arrester is used in connection with distributing transformers the burn-outs of the transformers are considerably reduced. His own records show that the burn-outs of transformers when a lightning arrester was used on the same pole are about one-third as great as when lightning arresters are not used upon the same pole. Now, a lightning arrester is merely a weak point (usually an air gap) which is used in close proximity to the transformer. I may call attention to the fact that a terminal board which is inside of a transformer serves the same purpose, it is a relatively weak point which lightning can break down. A great disadvantage of making the terminal board or connecting board the weak point is that when lightning does puncture at that point, it blows the fuses, and you have an interruption of service on that transformer, and that is admittedly an objectionable point. I do not believe that this demonstrates that we should not have a connection board above the oil in the transformer, but it should be a connection board having an amount of clearance which makes it, not impossible, but highly improbable, that the lightning will go across inside. That is to say, the design of such a terminal board should be such that it is as strong as the distributing line which is in immediate proximity to the transformer. If you have a terminal board of such a design, that is, so that lightning will go across on the outside of the transformer rather than on the inside, then I think any objection to the terminal boards is removed.

There is one point upon which I want to agree with Mr. Roper, and that is upon the use of fuses for overload protection. Mr. Roper states that the fuse cannot be relied upon an as overload protection, and I believe thoroughly in that point of view. The fuse, when it is used in connection with transformers, is primarily used for the purpose of interrupting short circuits or interrupting something which would cause the service to be interrupted at other points than that one particular transformer, and that is, I believe, its only function. I do not believe that it is possible to design and operate fuses upon our distributing transformers of such a nature as to protect them against overload. I think such a use of a fuse is practically out of the question.

I was very much interested in what Mr. Roper said about the accelerated life test. That is not a new idea, by any means, and if we could find some means of condensing the years into hours, in so far as the life of the transformer is concerned, we would be

very glad to get the results which we should get by such an accelerated life test, but so far, we have not been able to devise any means to accomplish that result, which we believe will be of very great value. If you run the transformer at double temperature for a day or two, that does not give the same result on this transformer as running it at moderate loads for several years; conditions are quite different, and whether the results obtained by overheating very considerably for a short period can be compared properly with the result of the normal life, is a very debatable question. Still, we are not giving up the question, and are still looking for some manner of accelerating the life of the transformer, so that we can crowd the life of the transformer into a few hours, instead of waiting for a good many years to elapse, to get information about the life of the transformer, such as we would have to do otherwise.

Joseph Franz: Representing one of the operating companies, I agree with Mr. Roper in general. Our troubles with the transformers in the Berkshires have been along the same line. Our experience in the matter of placing lightning arresters on the same pole with transformers has shown us that it is not always possible to obtain a good ground connection in isolated or remote sections, and we have had two cases where the lightning arresters failed. The current fused the gaps of a multiple-gap arrester and being connected on the same ground as the secondaries, this condition of the arrester sent the primary current into the building where the service was furnished, and set the building on fire. That caused considerable trouble to our company. Since we had this experience, we place no lightning protectors on the same pole.

Mr. Roper refers to the name-plate, and I would like to add that it would be an advantage to have the manufacturers standardize on the form of the name-plate, its arrangement, as well as having the reading matter in the same order, similar to the way in which the National Electric Light Association has standardized the meter dial faces, so that a man at a glance could read what he wished to read, without going over the whole name-plate.

In regard to the oil, I believe it would be better to adhere to the present practise of having the manufacturers furnish the oil, as it would be very difficult for the smaller companies to select the proper oil for the transformers, and last, but not least, in case of failure the manufacturers could not lay the trouble to improper oil, if it was furnished by them.

M. O. Troy: Actual failures of transformers in service are represented by a very small percentage, yet it is very important that this percentage be reduced in every way possible, as each breakdown may constitute a risk to person or property. Inasmuch as we are dealing with such small percentages, any mere discussion on the part of engineers as to what will or will not decrease this percentage cannot settle the matter, and we have to resort to actual statistics such as Mr. Roper has collected and presented.

In many of our electrical devices, such as the flat iron or incandescent lamp, failure merely means the loss of that device, possibly a little complaint, and replacement if it has not given the service expected of it, but no particular damage is expected or done. The distribution transformer, however, occupies a unique field in that it is supposed to supply these devices uninterruptedly, to take the high-voltage energy, transform it, and to permit the user to apply it to the various current-consuming devices with no misgiving and usually with no question as to safety.

Mr. Roper has pointed out, without resorting to theories or deductions, methods for obtaining greater safety and continuity of service, and has established his contentions by actual results of operation based on observation of hundreds of installations.

Mr. Fishel's plea for standardizationis timely—1100- or 1200-volt plants are rapidly going out of existence, and the time has now practically arrived when, for a large part of this work, we can establish one primary voltage in the neighborhood of 2200 or 2400 volts—possibly as a compromise 2300 volts. This will enable the manufacturers to do away with connection boards, or else to use connection boards merely as lead supports, and with such liberal spacings as will not, under any operating strains, permit failure of the board. If, for convenience in some cases, it is necessary to supply connection boards, my experience, based on observation of hundreds of thousands of units, conforms to Mr. Roper's—namely, that it is better to submerge the boards.

Referring to Mr. Lincoln's contention that in some instances the unsubmerged connection board might be advisable to act as a safety valve by arcing across, blowing the fuses, and disconnecting the transformer—it would seem that this pre-supposes that the transformer strains, from lightning or high frequency, are from one primary to another. Is it not true that the lightning strains are more frequently from primary to ground, and a relief of these strains, via the connection board, assumes that the lightning must, in some way, go from the connection board to the neutral of the secondary? Inasmuch as this method of breakdown is one of the very things we are trying to guard against, it would seem preferable to make the connection board, if it is used, as strong as possible, and to provide a safety valve—say lightning arresters—outside of the transformer.

Another objection to relying on the connection board to discharge high-frequency energy is that the discharge path consists merely of a small number of gaps with no resistance in series, and acts very much like an arcing ground, in that in the very act of relieving the strains, the arc itself may break down the windings.

A great many manufacturers are now carrying two lines of transformers within the voltage range under discussion, namely, 1100/2200 and 1200/2400-volt lines. It would be my recommendation that we supplant these with a line of one primary voltage—say 2300, with a density range in the core, making the

transformers satisfactory for operation under any range of voltage from 2100 to 2400; that we build the transformers as strong as practical consideration of costs, when balanced against results secured, will permit, and provide a safety valve in the way of a well-designed lightning arrester for use outside the transformer. This recommendation, I believe, embodies the standardization idea suggested by Mr. Fishel, and as far as I can see, is in conformity with the recommendations which might be made, based on the statistics submitted in Mr. Roper's paper, and deductions which may be made therefrom.

E. E. F. Creighton: Only those who have been through the experience of collecting a mass of data, and under the various and variable conditions such as exist on a large distribution system, realize how difficult it is, first of all, to gather reliable data, and next, to correlate these data in such a way as to draw any practical and useful conclusions. Breaking a path through any unknown region is always far more difficult than following one already made. The work of months can finally be expressed in a few brief tables and descriptions, giving no comprehension of the labor involved. Mr. Roper's information has been collected at a considerable financial outlay, and has called for careful organization of untrained men. From the standpoint of perfecting electrical protection, the investigation has a great value. It has done more than confirm the results of laboratory experiments. There has been added apparently a new conception of the nature of some surges which were considered harmless.

In the matter of deterioration due to successive strains in the accelerated life tests, it might be pertinent to state that such laboratory tests have been made. Mr. Roper's paper deals particularly with lightning, and in the duplication of lightning it has been possible in the laboratory to furnish any kind of a surge that is required—high frequency, high potential, steep wave front, sloping wave front, etc., and with these discharges, accelerated life tests were made on transformers. In conjunction with this, different types of lightning arresters have been tested out at the same time.

In such tests, applied to many transformers, we have found that there is a deterioration from successive discharges. In nearly every case the transformer is able to withstand more than one discharge. Of course, the number of discharges that the insulation will stand is dependent upon the severity of the discharge, that is to say, in general, upon the voltage and the steepness of the wave front. The tests have shown that successive discharges will deteriorate some types of insulation, in somewhat the same way that a nail is driven through a board by successive strokes of a hammer.

All the laboratory experiments confirm Mr. Roper's statement that there is a deterioration carried on year after year due to lightning.

Very recently Mr. DeBlois gave a paper before the Institute,

at Washington, in which he showed oscillograms of lightning strokes which have different wave fronts, and gave us a very good idea, so far as it goes, of the different kinds of lightning strokes which should be reproduced in the laboratory.

Briefly expressed, some of the salient points brought out by the data so far gathered are as follows: Doing away with exposed terminals reduces the troubles by one-half, placing arresters on the same pole with the transformers has still further reduced the trouble by one-third, and by further improvements in protection the troubles may be again decreased one-half, making a total of one-twelfth the present troubles. Since the total trouble was originally small, a reduction to one-twelfth makes the effects of lightning quite negligible.

The new conception of the danger from surges is furnished by the data which show that where a terminal board is exposed in such a way as to allow a lightning discharge to take place through the case, the transformer is not protected but actually damaged. Short circuits at the terminal of a transformer cut off the coils from the heating effect of the current. What, then, could damage the transformer coils but a surge? Mr. Roper's results show that one-third more transformers were damaged where the terminals were exposed than where they were not exposed. These data have important significance.

Summarizing the situation, all the information collected to date would impose the following practise for the protection against lightning:

First: Have no exposed terminal boards. By that I mean the discontinuance of the practise of using a terminal board as any sort of protection for the transformer.

Second: Place the arrester on the same pole with the transformer. The objection brought up by one of the speakers that different grounds should be used is pertinent, but that has nothing to do with placing the lightning arresters on the same pole with the transformer, as two separate grounds can still be used where desired, and in every case it seems to me desirable to have a gap between the lightning arrester ground, and the ground on the secondary of the transformer.

Third: Use an arrester with good protective qualities. These practical investigations Mr. Roper has made have given us information on the nature of the lightning strokes, that is to say, the percentage of low-frequency strokes to high-frequency strokes, and steepness of the wave front, and therefore we are able today to choose the factors in a lightning arrester to better advantage than ever before.

Fourth: Ground the transformer case to the ground terminal of the arrester, through a gap if desired. Although many engineers differ from this conclusion, my own tests have shown that connecting the case to the ground terminal of the arrester gives a valuable improvement in the protection, in that it makes the protective element of the arrester more nearly independent of the resistance of the earth connection.

There are many places where it is absolutely impossible to get a good earth connection. It has been pointed out that the object in protection is not necessarily to reduce the lightning potential to ground potential, but to prevent a great difference of potential from the primary to the secondary and case. If the lightning arrester is connected from the primary to the case, and through a gap to the secondary, then it is possible to have the transformer, say, at 200,000 volts above ground potential, with only a difference of potential from the primary to the secondary and case of about 6000 or 8000 volts. This point of connecting the lightning arrester to the case is, I believe, the solution of the problem presented by high-resistance earth connections. Furthermore, it eliminates the inductance of 30 ft. of line from the transformer to the ground. It has been demonstrated in practise, by many years of experience, that a short length of line, even the distance from the transformer to the next pole, introduces in the arrester circuit sufficient inductance to greatly decrease the protection of the transformer. Therefore, it is reasonable to conclude that the 30-ft. length from the transformer to ground is also objectionable.

H. B. Alverson: Mr. Roper's paper has pointed out very definitely the troubles occurring with the transformers and the fuses. It is very evident that the transformer ought not to be a lightning arrester, and this one point would argue for a change in the matter of terminal boards in the transformers.

The question of lightning arresters on the same pole with transformers is a very difficult one in city work, where you have joint line construction, and you are compelled to use the same poles with, perhaps, two other telephone companies. The use of a number of lightning arresters on a circuit is bad practise, in case of trouble, when you have to look up the source of trouble. A limited number of lightning arresters properly placed will do as much good, and trouble is easier to locate, than with a greater number of lightning arresters connected with your distributing transformers.

As to the question of fuse box, I believe with Mr. Roper, that that question should be considered entirely separate from that of transformers. The question of the fuse box can be better determined by the nature of the work outside, and the method of locating them on the poles.

W. L. Granger: Nearly two years ago we undertook to standardize our transformer connections, that is, we removed the terminal boards. Of course, the conditions in Detroit are such that it leaves us with a pretty clear course, in other words, there are two entirely independent systems, one operating at 4600 volts and the other one at 2300 volts. We find that we are getting very good results from the change.

In regard to Mr. Lincoln's remarks relative to the proper dimensions of the terminal block at the oil level, it appeared from our experience that the dimensions were of comparatively little

consequence; that is to say, if you had a transformer located in the manufacturing district where there was a lot of smoke and coal soot, the transformer in time is bound to breathe in more or less of this soot and smoke. We found in the summer time that the oil would evaporate and there would be some moisture on top of the block, and this soot and smoke would go right in on it, and it did not seem to make much difference, after a time, what distance you might have between these terminals on the primary side of the transformer. In other words, we found the transformers would break down across the block, due to losses on the lines, in the winter time, even, when there was no lightning, so that we are taking the connection boards out entirely and ordering our new transformers without the blocks at all.

In regard to lightning arresters, I quite agree with Mr. Roper on his proposition of furnishing a lightning arrester for each transformer. It appears, after some observation on my part and some little experience, that this will probably solve the problem.

As to the matter of lightning arresters that break down in service, causing arcing grounds on such a line, last summer I inserted in the line side of the lightning arrester unit a fuse which was a piece of No. 18 copper wire inside a glass tube. It was a very inexpensive affair, placed away from the lightning arrester itself, so that the terminal leading from the fuse into the box is a flexible piece of wire. We have had fairly good success with this device, so that what we are doing this year is to put in these fuses in all of our multi-gap arresters.

W. J. Wooldridge: There are three principal points to which we must look in order to insure reliability of transformers. Two of these points have been touched on, the first being the design, which includes the proper proportioning of insulation and arrangement of cords and connections, etc.; the second being the actual manufacture; and the third being the insulation and protection of installed apparatus.

It is a little out of line, perhaps, with what has been discussed, but I would like to say a word on a certain point, and that is the actual point of manufacture.

It is very essential, of course, that the insulation should be kept intact. The engineer must allow a certain margin of safety when he figures on the amount of insulation to be put in, and part of that margin of safety is to be allowed for possible accidents in the installation; but a great deal depends upon the careful handling of the insulation by the workmen. The workmen, in order to be taught to properly handle the insulation, cannot be successfully reprimanded or coerced, they must be coaxed and trained into understanding the full value of insulation; and in order to put the workmen into a proper frame of mind, the idea of "safety first" has to be thoroughly carried out. The workman must be made to understand that he, too, is being looked after in the same way that he must look after the material.

D. W. Roper: Mr. Moody in opening the discussion brought out the point that co-operation such as is shown in this paper, was desirable. We sometimes have the same difficulty in getting the co-operation of some of our customers—they expect us to relieve them of their troubles without knowing anything about them, and it is only after being properly informed of the troubles which occur that we can take steps to remedy or eliminate them.

On the question of connection boards, on which there was quite a little discussion, the conclusions as reached in the paper were criticised, and it was suggested that an improved design of connection board would have shown quite different results. That is very true, but in the case of an operating company which has no use for a connection board, it does not appeal very strongly to them to experiment in trying to eliminate the difficulties in the connection board, if they can as well eliminate the connection board itself. In Chicago the present practise in purchasing transformers is to remove them before they are placed in service, and in addition, the transformers which come into the storeroom due to changes, such as increase in capacity, or to removals, or changes in location, or other contingencies of that kind, have their connection boards removed before again going out on the line.

The point was raised that Tables IV and V referred to transformers of quite different ages. That is very true. The ages of the various transformers were quite different, and the difficulty was recognized of properly allowing for the difference in age in making up the curves which are shown in these tables. However, if such an allowance had been made it would have served to accentuate the differences shown in the table.

The point was raised of the difficulty of installing lightning arresters on the same pole with transformers on account of the necessity of having a separate ground for the lightning arrester and the transformer secondary. That is a point which comes up frequently, but we have settled it for our purpose by installing the lightning arrester ground on the same pole with the transformer, and installing the secondary ground on a different pole. In most of the installations the transformer secondary serves a number of customers, so we can just as well put the secondary ground on the adjacent pole. Where necessary we string in an additional span of the secondary neutral wire for the purpose of removing the secondary ground to the next pole, and getting it away from the lightning arrester ground.

The question was raised of the additional troubles which would be experienced with the large number of lightning arresters. Our experience with several types of lightning arresters is that, on the whole, the lightning arresters of the present day give comparatively few interruptions to service, and that they are almost as reliable, as far as freedom from interruption of the service is concerned, as the transformers themselves. These remarks do not refer at all to their value as protective devices, but refer to their vulnerablity, as you might call it, or their danger as a source of interruption.

A point was also raised about the grounding of transformer cases. This matter was not mentioned in the paper, not because we have no installations of that kind, but because they have not been in service long enough to have given us any different experiences to report. We have about six hundred transformers whose cases are grounded on three different circuits, and we are trying to keep our records, so we will have some practical experience along that line.

The statement was made that there was some difficulty in getting proper grounds where joint pole line construction was used. A large proportion of the distribution in Chicago is on pole lines jointly owned. The worst that can happen in such a case is that the telephone company may locate a ground for their aerial cable sheath on the pole that you afterwards select as a transformer pole, and the solution of that difficulty is to pay them to remove it to the next pole.

The point was raised that an arrester on each transformer was not necessary. That is true; it is merely a question of the quality of service which the company desires to supply to its customers. With a small number of lightning arresters they can give one grade of service, and with a larger number of arresters they can give a little higher grade. If the smaller number of arresters is sufficient to supply the demand in your particular city there is no object in incurring the additional expense of the larger number of arresters.

Presented at the 296th Meeting of the American Institute of Electrical Engineers, Pittsfield, Mass., May 28, 1914.

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INHERENT VOLTAGE RELATIONS IN Y AND DELTA CONNECTIONS

BY ROYAL W. SORENSEN AND WALTER L. NEWTON

ABSTRACT OF PAPER

The paper gives the results of experiments made with a miniature simple transmission system to demonstrate the inherent voltage relations with different combinations of Y and delta connections.

The experimental system consisted of a 7.5-kv-a. revolving field generator, with coil terminals which could be connected either Y or delta, and two banks of transformers each composed of three shell-type 3-kv-a. units. All inductive and capacity effects in the transmission line were eliminated. The tests were made under constant conditions, with non-inductive load.

The authors give the results of four groups of tests, on four different systems of connections, pointing out the advantages and disadvantages of the several systems. In each case tests were made without load, with balanced load, and with load on one phase only, for various conditions of grounding. Typical voltage diagrams are given, to show what happens under various conditions of load.

The authors discuss certain cases where the use of auto-transformers is advantageous, and the effects of different ways of connecting them.

THE HIGH survival value which the subject of Y and delta systems has as a matter of discussion almost warrants the assumption that inherently neither system can be said to be generally inferior to the other for the transmission and distribution of electric energy. On the other hand, if there is to be any choice of either system, even for special work such as long-distance transmission at high voltage, it would seem as though the choice must be based upon certain features inherent in the method of connections, even though these features may not in themselves be bad, but rather become conducive to trouble only when combined with other features incident to that particular condition.

It is the purpose of this paper, therefore, merely to bring to the attention of those interested, experiments made with simple Y-connected and delta-connected systems and to show, if possible, wherein the advantages of one with respect to the other may lie.

The simplest system which could be constructed would be

that of a single three-phase line supplied at one end through step-up transformers by the generator and at the other end giving out its energy to the connected load through a bank of step-down transformers.

As there can be made with each three-phase bank of transformers four combinations of connections, and as the generator and the receiving motor may be connected either Y or delta, it is readily evident that even in a very simple system there may be made a large number of combinations.

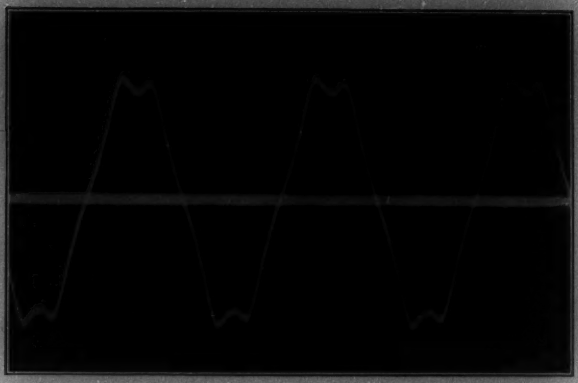
The generators as a rule are connected Y because of the better wave form obtained, as seen in Figs. 1 and 2, and because of the convenient ground point which is then provided. Experience has practically made standard the delta connection for the low-tension windings of both the step-up and step-down transformers, thus leaving for consideration only the arrangements of the high-tension windings of step-up or step-down transformer banks. These may both be connected Y, as has been very generally done, and the neutral points may be grounded or not grounded, the grounded condition being, however, the one in general use. They may both be connected delta or one may be connected delta and the other connected Y, a condition not usual, but one which in some cases has been thought desirable.

Having made a selection as to the arrangement to be adopted in any particular system, it is of course obvious that this system must be carried throughout for any points of multiple connection of transformer banks or transmission lines, because of the impossibility of delta-Y banks being run in parallel with delta-delta banks.

Description of Tests

To determine the inherent relations, a miniature system consisting of a 7.5-kv-a. revolving field generator, with coil terminals brought out so that it could be readily connected Y or delta, and two banks of transformers each consisting of three shell-type 3-kv-a. units, was constructed. All inductive and capacity effects in the transmission line, which was in this case only the necessary leads for connecting together the high-tension windings of the step-up and step-down transformer banks, were entirely eliminated. This must be kept in mind when considering the conclusions drawn from the tests.

All tests were made for constant conditions and the load used was non-inductive. Potentials were measured with a multicellular electrostatic voltmeter, which on closed circuits



[SORENSEN AND NEWTON]

FIG. 1—VOLTAGE CURVE, CENTRAL LABORATORY ALTERNATOR. 110 VOLTS, 50 CYCLES. DELTA-CONNECTED.

[SORENSEN AND NEWTON]

FIG. 2—VOLTAGE CURVE, CENTRAL LABORATORY ALTERNATOR. 110 VOLTS, 50 CYCLES. Y-CONNECTED.

was carefully checked with a standard portable dynamometer instrument.

All connections were carefully insulated from each other and from ground, as was also the frame of the generator, except

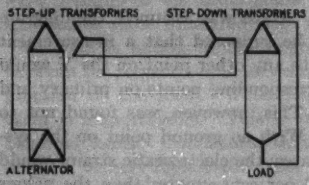


FIG. 3

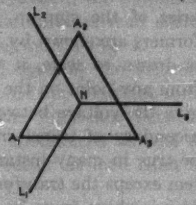


FIG. 4

in such cases as it was well grounded with a copper ground. In all tests the transformer cores and cases were well grounded.

The first group of tests was made on the system connected as in Fig. 3, without load, with balanced load, and with load

TABLE I*

Load	Gr'd point.	Open point.	Maximum per cent volts.				
			H. T. to Gr'd. % H. T.	L. T. to Gr'd. %L. T.	H. T. to L. T. % H. T.	H. T. to L. T. % L. T.	N. to Gr'd % H. T.
0	None	None	57.7	57.7	82.0	163.0	0
0	Neutral	"	"	"	"	"	"
Balanced	None	"	"	"	"	"	"
"	Neutral	"	"	"	"	"	"
1 phase	None	One H.T. line	51.0	69.5	90.0	180.0	18.2
"	Neutral	"	73.0	167.0	138.0	276.0	0
"	None	One load lead	74.5	70.0	100.0	200.0	4
"	Neutral	"	62.4	71.5	104.0	209.0	0
Balanced	One H.T. line	None	100.0	65.0	—	—	—
	N & 1 " "	"	91.2	57.7	—	—	0

*In these tables readings with ungrounded generator frame are omitted (exceptions noted in Tables II and IV), as this condition so rarely exists in practise.

on one phase only, for various conditions of grounding. Some typical results of these tests are shown in Table I. When one phase only is loaded, such condition is obtained in one of two ways: by opening a high-tension line, or by opening a low-tension line on the load end.

Fig. 4 shows the no-load voltage diagrams of high- and low-tension lines superimposed upon one another. The step-up and step-down transformers being identical, the delta represents voltages of generator, primaries of step-up transformers and secondaries of step-down transformers. Line voltages, secondaries of the step-up, and primaries of the step-down transformers are shown by the Y. If, as was assumed, the diagram is drawn to scale, it would be supposed that a measurement from any point on the delta to any other point on the Y would give the voltage between corresponding points on primary and secondary of transformers. This, however, was found not to be true in many instances. With no ground point on the system except the transformer cases, the electrostatic strains would be anywhere from 50 to 100 per cent greater than the values obtained by measurements from the diagram. The neutral point of the Y, which should normally be at ground potential, was found to be at some distance above. It was in fact found

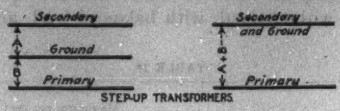


FIG. 5 FIG. 6

that no point on the entire system was exactly at ground potential, except of course the transformer cases, and even the frame of the alternator was found to be at a potential above ground greater than normal line voltage. These facts can lead to but one conclusion, namely, that the conditions on all systems cannot be truly represented on one plane.

On this assumption, a great number of readings were taken, and it was found that each section of the system might lie in a totally different plane, but that these planes are always approximately parallel.

An end view, then, of Fig. 4 would appear as in Fig. 5, in which each line represents the plane on which the respective diagrams would have to be drawn to represent correctly the readings obtained. No definite law seems to govern the relative position of these planes. On one day the distance between them may be twice that obtained on another. However, the primary and secondary planes are always on opposite sides of ground, as shown.

The grounding of the Y neutral brings the transmission line plane to ground potential, but maintains a nearly constant potential between this plane and the generator plane, so that the potential between generator plane and ground is doubled, as in Fig. 6. When the generator frame, which heretofore had been well insulated, was thoroughly grounded, all potentials were brought to the same plane and the voltages read corresponded to those measured from the diagram, in Fig. 4.

As load is added to the ungrounded system, the distance between the respective planes decreases, and appears to be some function of the load. When loaded, the difference between them is inappreciable. This is true of unbalanced as well as balanced loads. Conditions, then, are better at load than at no load, or very light load. (See Table I.)

The second group of tests was made with the same trans-

TABLE II

Load	Gr'd point.	Open point.	Maximum per cent volts				
			H. T. to Gr'd. % H. T.	L. T. to Gr'd. %L. T.	H. T. to L. T. % H. T.	H. T. to L. T. % L. T.	N. to Gr'd % H. T.
† 0	None	None	57.7	61.0	85	167.0	0
Balanced	"	"	"	"	"	"	"

†Generator frame not grounded.

former arrangement but with the generator connected Y. The tests made under these conditions gave results as in Table II, which are very similar to those of the first group, in that there still remains the tendency for the voltage planes to separate on the ungrounded system, at light load. This condition is probably better, however, than the first, due to the better wave shape obtained with the generator in Y, as can be seen by a comparison of Figs. 1 and 2.

From these data the following conclusions for a Y-connected transmission line may be drawn: The generator should be connected Y. The neutral point should be well grounded at both ends to relieve electrostatic strains. There is, of course, the objection to a grounded neutral, that if a line becomes grounded also, one phase is short-circuited. The second point, which fortunately does not often arise in practise, is that all alternator frames, motor frames, and transformer cases should

be thoroughly grounded, not only for the foregoing considerations, but also to protect the lives of operators and linemen.

The disadvantages of Y-connected transmission lines may be summed up: Difficulty of obtaining a satisfactory ground on the neutral, and overload or short circuit of one phase by partial or complete grounding of a line.

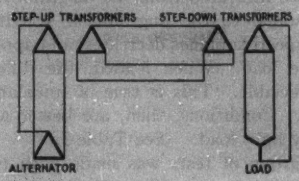


FIG. 7

The third group of tests was made with the system connected as in Fig. 7, with the same load conditions as in the previous set of tests. With this arrangement the normal stresses are about the same as with the Y connections (see Table III), and the unbalancing of load causes no serious variation in voltage relations, but there remains the tendency for the circuits to

TABLE III

Load	Gr'd point.	Open point.	Maximum per cent volts.				
			H. T. to Gr'd. % H. T.	L. T. to Gr'd. %L. T.	H. T. to L. T. % H. T.	H. T. to L. T. % L. T.	N. to Gr'd % H. T.
0	None	None	58.3	57.7	91.2	105.0	—
Balanced	"	"	"	59.0	"	"	—
1 Phase	"	OneH.T. line	60.1	60.1	104.0	120.0	—
"	"	One load lead	65.0	67.2	109.0	126.0	—
0	OneH.T. line	None	100.0	64.5	135.0	156.0	—

lie in different planes, which separate decidedly with a removal of the ground connections to the generator frame. In this case, again, the bad wave form of the alternator connected delta is objectionable. On the whole this system is not to be recommended, as conditions seem to be particularly unstable, and there is no possibility of obtaining a ground point if occasion demands.

The fourth group of tests was made with the same transformer connections as in group three, but with the generator connected Y, giving the better wave form. This is apparently the ideal condition, as with such an arrangement it is unnecessary to ground this neutral in order to relieve abnormal elec-

TABLE IV

Load	Gr'd point.	Open point.	Maximum per cent volts.				
			H. T. to Gr'd. % H. T.	L. T. to Gr'd. %L. T.	H. T. to L. T.		N. to Gr'd % H. T.
					% H. T.	% L. T.	
† 0	Gen. N. (Ng)	None	58.7	57.7	94.4	109.0	0
"	None	"	58.2	"	"	"	3
Balanced	Gen. N.	"	57.7	60.0	"	"	0
1 Phase	"	OneH.T. line	71.7	90.0	167.0	192.0	4
"	"	One load lead	81.2	84.0	142.0	164.0	"
0	1 H. T. line & Ng	None	100.0	58.0	145.0	167.0	"
"	OneH.T. line	"	"	63.7	148.0	168.0	"
Balanced	1 H. T. line & Ng	"	"	58.0	145.0	167.0	"

†Generator frame not grounded.

trostatic strains between windings. (See Table IV.) All neutral points remain close to ground potential, even under unbalanced load. There being no grounded neutral on the system, the danger of a short-circuited phase by grounding is entirely obviated, unless two lines should become grounded simultaneously.

Voltage Diagrams

A few voltage diagrams might help to make clear just what happens under various conditions of load. To avoid needless repetition of similar figures, diagrams of the results obtained in the fourth group of tests are taken as typical.

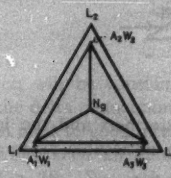


Fig. 8

Fig. 8 represents conditions under balanced load, in which the Y is the generator diagram, with the neutral at Ng. The delta A_1, A_2, A_3 represents the primaries of the step-up bank of transformers, and L_1, L_2, L_3 the secondaries of this bank and the primaries of the step-down transformers. The diagram of the secondaries of step-down

transformers connected in Y, corresponds to A_1, A_2, A_3 and is indicated by W_1, W_2, W_3.

If, now, one line is opened between step-up and step-down transformers, conditions result as in Fig. 9, which is lettered to correspond with Fig. 8. The heretofore symmetrical figures become considerably distorted. W_1, W_2, W_3 becomes a straight

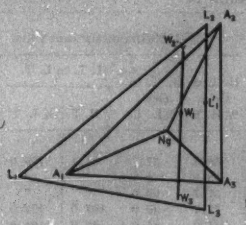


FIG. 9

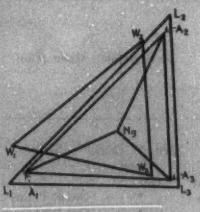


FIG. 10

line, and is therefore in series from W_2 to W_3. The diagrams of the secondaries of the step-up bank and of the primaries of the step-down bank of transformers are no longer coincident. The former is shown by the triangle L_1, L_2, L_3 and the latter by the straight line L_2, L_1', L_3. The distance L_1-L_1' represents the voltage across the open switch.

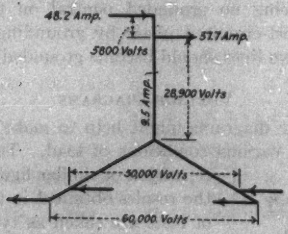


FIG. 11

An open line between step-down transformers and the load gives Fig. 10. The distortion is not so noticeable as in the previous case.

AUTO-TRANSFORMERS

The economic advantage of using auto-transformers for changing from one phase to another and for making slight

voltage changes when it has not been necessary to keep the two systems insulated from each other, has caused them to be quite extensively used.

Example: A certain large power company had as one source of supply a plant which delivered power to the main distribution center, over a 125-mile (201-km.) line, at a potential of 50,000 volts. In the new development 60,000 volts was selected

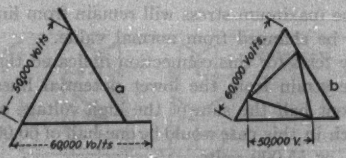


FIG. 12

as a standard for long distribution feeders, and as the line insulation would not permit the old system to be raised to this voltage, the two projects were tied together by means of three auto-transformers, which were Y-connected and would carry, on the 50,000-volt taps, 5000 kv-a. The connections and currents for this bank of auto-transformers are shown in Fig. 11.

This is the most common arrangement of auto-transformers because it is both convenient and economic, and the only one

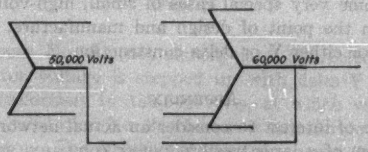


FIG. 13

which will be considered, although either the extended delta or the delta connection as shown in Fig. 12, *a* and *b*, might have been used to good advantage.

When such an auto-transformer is used, it is connected as in Fig. 13. For such an arrangement there may be two conditions; grounded neutral and ungrounded neutral. With grounded neutral the triple-frequency e.m.f. which exists from line to ground may become very dangerous, particularly if the line has

considerable electrostatic capacity, as would be the case in the assumed problem, because of the intensifying effect of the third harmonic in the charging current. In some tests made, the maximum stress was found to approach three times normal potential for the neutral of the auto-transformer bank grounded.

With the neutral of the auto-transformer bank ungrounded, stresses running up to 50 per cent of line voltage may be measured from ground to neutral, which is of course not a serious matter, as the maximum stress will remain from line to ground and will not be changed from normal value.

Laboratory tests for this connection indicated that the maximum voltage strain from the lower potential lines to ground would be about half the sum of the high-voltage and the low-voltage, which in this case would be one-half of 60,000 volts plus 50,000 volts, or 55,000 volts.

Transformer Design

When transformers were made in small sizes only, particularly if they were shell type, there was some advantage in having the windings connected Y for the high-tension side of the bank, as this allowed a smaller number of coils and less insulation, because the normal strain was 57.7 per cent of that of delta-connected transformers. The increase in size of units and the provision for maximum strain where one line becomes grounded have made these economic advantages obsolescent, except in some very special cases of small, high-voltage units. Hence, from the point of design and manufacture, there is no advantage for either Y or delta construction.

Appendix

It may be of interest to consider an actual network diagram of the system of a large western power company, as shown in Fig. 14. The following nomenclature is used:

A, engine-driven alternator.
TA, turbine-driven alternator.
T, transformers.
AT, auto-transformers.

The numerals indicate the voltage at various points on the system. For simplicity, the location of switches has not been shown. Several small generating stations on the system are not shown.

Power house No. 1 contains three (shown as one in diagram) engine-driven alternators delivering power at 15,000 volts directly to the busbars. The two turbo-generator sets generate at 9000 volts and step up to the busbar voltage through auto-transformers. In substation No. 1 this is stepped up through transformers to connect with a 50,000-volt line, and in substation No. 2 it connects with a 60,000-volt line through transformers.

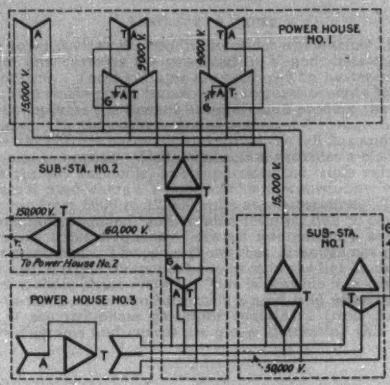
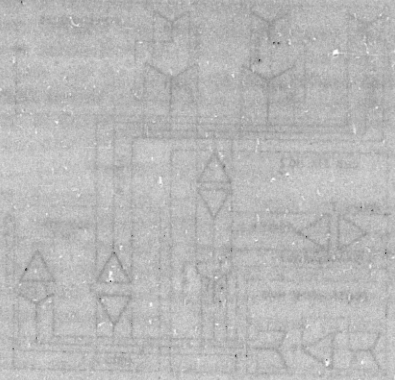


FIG. 14

Power house No. 2 (not shown) is a hydroelectric plant. The generator voltage is stepped up with delta-Y (grounded neutral) transformers to 150,000 volts, at which voltage it is delivered to substation No. 2, where it is transformed to 60,000 volts as shown. The 50,000-volt line from power house No. 3 is connected to the 60,000-volt line through auto-transformers. Substation No. 1 contains a bank of transformers connected Y-delta, with the neutral grounded and the secondary on open circuit.



Presented at the 296th Meeting of the American Institute of Electrical Engineers, Pittsfield, Mass., May 28, 1914.

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HARMONIC VOLTAGES AND CURRENTS IN Y- AND DELTA-CONNECTED TRANSFORMERS

BY R. C. CLINKER

ABSTRACT OF PAPER

The paper reviews the conditions under which triple harmonic voltages and currents are produced in Y-and delta-connected transformers. These voltages are produced by hysteresis in the core. In a single-phase transformer, increase of series resistance tends to suppress the current harmonic and produce the voltage harmonic. In three-phase transformers, a Y connection suppresses the current harmonic and allows the full flux and voltage harmonics to appear. Delta connection provides a closed path for the current harmonic, and suppresses the triple voltage.

A case is cited where a Y-connected auto-transformer was used to step up from 6600 to 12,000 volts at a substation. The neutral was not grounded, and trouble resulted due to partial resonance at triple frequency between line capacity and transformer reactance. The paper shows that, although not generally recognized, a triple component can exist in the line-to-line e.m.f. wave of a three-phase system. This is possible in a case where a two-to-three-phase transformation is used, and when the e.m.f. wave of the two-phase generator contains a triple harmonic. Vector diagrams and curves are given illustrating this possible effect.

IN CONSIDERING the relative advantages and disadvantages of Y and delta connections of transformer windings, it is necessary to pay some attention to the production of harmonic voltages and currents occurring in such windings due to hysteresis in the core. This has been treated by several since the present writer first drew attention to the effect,[1] but it may not be out of place in the present discussion to review briefly the conditions under which such harmonics become noticeable, and to point out a further possible case which, so far as the writer is aware, has escaped notice.

If we take the case of a transformer winding connected to an a-c. source of supply, we find that though the e.m.f. wave may be sine-shaped, the current wave necessary to produce the sine flux wave contains harmonics, notably a third and a fifth, which are produced by hysteresis and by the variation of permeability of the iron. These current harmonics may be regarded as in-

1. See the *Electrician* for 10th November 1905 and 5th January 1906.

duced in the circuit by harmonic flux variations arising in the core. In such a case, however, the current harmonics produced "wipe out" almost completely the flux harmonic, because the resistance of the circuit is usually low. Hence the value of flux harmonic actually existing is only that sufficient to induce a voltage in the coil equal to $i \times r$, where i is the harmonic current, and r the resistance of the winding. By increasing the resistance, however, the flux and voltage harmonics become very noticeable, and a distorted wave form appears across the coil terminals. (Incidentally, this has an important bearing upon the use of series resistance for varying the voltage of an insulation-testing transformer, which sometimes results in the production of a high peak voltage. One remedy is to shunt a resistance across the transformer terminals, which allows of the use of a lower series resistance and therefore, reduced distortion). Without increasing the resistance, however, there is another way by which the current harmonic may be suppressed, viz., by the use of a star-connection of circuits, using the term "star" in its general senses implying n circuits for an n-phase system. A little consideration shows that the nth harmonic of e.m.f. induced by the iron is directed in each circuit simultaneously towards or away from the neutral point, and that therefore no current of this frequency can flow. Hence, with a three-phase Y connection, the triple component of the magnetizing current is eliminated, and the full triple-frequency flux variation occurs, producing a distorted wave form of high peak value, across each winding. With a Y-Y connection of transformers, particularly with single-phase transformers or shell type three-phase transformers, the full flux variation occurs. In the case of one set of windings, either primary or secondary, being delta connected, the flux variation is almost wholly suppressed by the circulation of the triple-frequency current in the closed triangle. From this point of view, therefore, a delta connection on either primary or secondary is desirable, as (1) It avoids the extra insulation stress due to the higher peak voltage, and (2) In the case of a transmission line with grounded neutral, it prevents triple-frequency capacity current in the ground wire, which, in the case of long transmission and high voltage, may reach a high value. In core-type three-phase transformers, the triple-frequency voltage is not marked, as the magnetic circuit of the flux harmonic is a partly open one, the path being up the three limbs in parallel and back through the air or tank. Oscillograms showing the

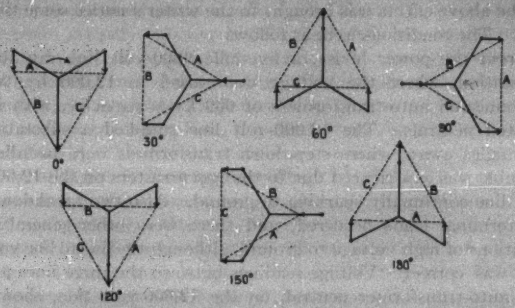
conditions obtained in various cases were presented in an interesting paper by Mr. J. J. Frank, before the A. I. E. E. in May 1910. A case where trouble occurred which could only be ascribed to the above effects was brought to the writer's notice some time ago. The conditions were as follows:

From the power house, a five-mile 6600-volt line ran to a substation, where the voltage was raised to 12,000 by two Y-connected auto-transformers of 600 kv-a. capacity, with insulated neutrals. The 12,000-volt line supplied a substation five miles away, where step-down transformers were installed. Trouble was experienced due to the gap arresters on the 12,000-volt line continually sparking to ground. Also two breakdowns on terminal leads occurred, and there were other general indications of high voltage to ground, although the line to line voltage was correct. Voltage readings between the three lines and the auto-transformer neutral, on the 12,000-volt side, showed that with normal phase voltage on the transformer and the 12,000-volt line disconnected, the pressure between each 12,000-volt terminal and neutral was 17 per cent greater than the phase voltage $\div \sqrt{3}$. When the 12,000-volt line was switched on, the voltage to earth rose further to 33 per cent above the normal value. Grounding the neutral of the auto-transformers cured the trouble, and reduced the voltage between the 12,000-volt lines and the ground to normal. It should be noted that the neutral of the generators was grounded through a low resistance at the power house. A ready explanation of these effects is afforded when the triple-voltage harmonics induced in the transformers are taken into account. With 12,000-volt lines disconnected, there is a 17 per cent increase of voltage to ground due to triple harmonic. This is aggravated, however, when the 12,000-volt line is connected, due to partial resonance, the capacity being in series with the high reactance of the auto-transformer winding. In this case the circuit is completed through the grounded generator neutral and the 6600-volt line. The effect of grounding is to connect the neutrals of generator and auto-transformer, and allow the triple component of current to be supplied, thus eliminating the voltage harmonic.

It has sometimes been stated[2] that no triple harmonic can exist in the e.m.f. between the lines of a three-phase system. It appears to the writer, however, that, though not often met with

2. See Steinmetz, paper before N. E. L. A., June 1907, also Rhodes, TRANS. A.I.E.E., 1910.

in practise, such an effect is quite possible. Consider the case of a two-phase generator supplying a three-phase line through Scott-connected transformers, and suppose that the generator



FIGS. 1-7—DIAGRAMS SHOWING TRIPLE HARMONIC IN THREE-PHASE SYSTEM AS PRODUCED BY THREE-PHASE GENERATOR OR BY Y-CONNECTED TRANSFORMERS—DOTTED TRIANGLE SHOWS LINE-TO-LINE E. M. FS.

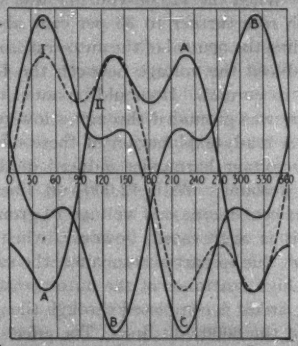


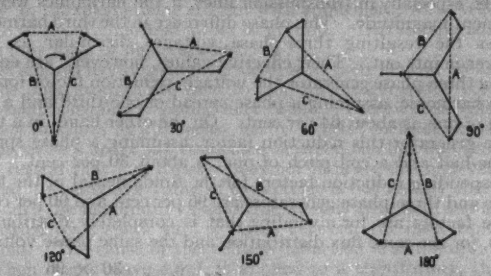
FIG. 8—WAVE SHAPES OF E. M. FS. BETWEEN LINES OF THREE-PHASE SYSTEM, SHOWING TRIPLE HARMONIC TRANSFORMED FROM TWO-PHASE SYSTEM.

Curves I and II two-phase e.m.fs. Curves A, B and C three-phase e.m.fs. See Figs. 9-15 for vector diagrams.

e.m.f. waves contain triple harmonics. As the main waves differ by 90 deg. in phase, the harmonics in the two phases will differ 3×90 deg. or 270 deg. in phase, *i.e.*, they will be in quadrature. Hence we have a two-phase supply at triple frequency

impressed upon the primary, and this is transformed to a three-phase e.m.f. at triple frequency, which appears between the lines as a superposed harmonic on the fundamental three-phase e.m.f. It is a curious fact that this effect cannot be obtained by direct three-phase generation, but, apparently, only by transformation from a two-phase supply. The accompanying diagrams will make clear the difference between the two cases, viz., (1) Triple harmonic due to three-phase generator, or Y connection of transformers. Harmonic appears only between line and neutral, and not between lines. Figs. 1 to 7 show the vectors at progressively varying phases, during one-third of a cycle.

(2) Triple harmonic impressed on system by two- to three-phase transformation. Harmonic appears both between lines,



FIGS. 9–15—VECTOR DIAGRAMS SHOWING TRIPLE HARMONIC TRANSFORMED INTO THREE-PHASE SYSTEM FROM TWO-PHASE SYSTEM. (SEE FIG. 8 FOR WAVE SHAPES.)

and between each line and neutral. Fig. 8 shows the three-phase waves produced between lines, assuming particular values for the amplitude and phase of the triple harmonic in the two-phase e.m.f. Curves I and II are the assumed two-phase waves, having exaggerated harmonics. A, B, and C are the resulting three-phase line voltages. Note that these waves are dissimilar.

Figs. 9 to 15 give the vector diagrams corresponding to Fig. 8. The dotted line A, representing one of the three-phase line voltages, also represents by its projections on vertical and horizontal the two-phase voltages I and II respectively.

The writer is not aware of any previous reference to this possible effect, and it would be interesting to hear if such has been observed on any line employing two- to three-phase transformation.

DISCUSSION ON "INHERENT VOLTAGE RELATIONS IN Y AND DELTA CONNECTIONS" (SORENSEN AND NEWTON) AND "HARMONIC VOLTAGES AND CURRENTS IN Y- AND DELTA-CONNECTED TRANSFORMERS," (CLINKER), PITTSFIELD, MASS., MAY 28, 1914.

Waldo V. Lyon (by letter): The interesting fact that Mr. Clinker notes in regard to the possibility of a third-harmonic voltage existing between the lines of a three-phase circuit was observed by the writer some time since, and was used as the basis of one of the problems in a collection* recently published by him. These third-harmonic components in the line voltages are equal but differ in phase by 120 degrees (third-harmonic scale) so that the circuit should respond to their influence in the same way that it would if sinusoidal voltages of three times the fundamental frequency were impressed upon it. This might produce serious results, especially in transmission lines, if the harmonics were of sufficient magnitude. This phase difference in the third harmonic makes the resulting three-phase voltages, dissimilar as Mr. Clinker points out. Their effective values, however, are equal.

In a three-phase generator the voltage reduction factor for the third harmonic, assuming a phase spread of one-third and a coil pitch of one, is about 64 per cent. On the other hand, in a two-phase generator this reduction factor, assuming a phase spread of one-half and a coil pitch of one, is about 30 per cent. The corresponding reduction factors for the fundamental in the two-phase and three-phase generators are 96 per cent and 90 per cent. These factors are for a winding that is completely distributed. Thus, for the same flux distribution and the same phase voltage, the third harmonic component would only be $\frac{30 \times 96}{90 \times 64}$, or one-half as great in a two-phase generator as in a three-phase generator.

A. E. Kennelly and Harold Pender (by letter): In connection with Mr. Clinker's observation on a rise of pressure of 37 or 33 per cent in different cases, attributable to partial resonance, with triple harmonic frequency, we may mention that on an artificial line at the Massachusetts Institute of Technology, built to represent a three-phase aerial three-wire 500,000-circular-mil conductor system 240 miles long, a voltage rise of 20:1 was observed experimentally by us at a frequency af 189~ which is substantially a triple harmonic frequency to the standard frequency of 60 ~. That is, when this length of artificial line was operated with 50 volts at the generating end and with 189~, the voltage at the distant free end reached 1000 volts, and this result checks very well with the theoretically deduced value.

*"Problems in Alternating Current Machinery," Problem 10, p. 127.

The application of the above-mentioned result to voltage regulation on a fairly long transmission line will be evident in the case of a voltage containing a high harmonic to which the line may happen to be a quarter wave length. For example, a line 240 miles long would be roughly quarter wave length to a third harmonic in a 60-cycle generator voltage wave. A five per cent harmonic at the generator would produce a 20 × 5 equals 100 per cent third harmonic at the receiving end at no load and so might produce, in combination with the fundamental, a peak voltage of twice the peak voltage at the generator.

F. W. Peek, Jr.: I was much interested, in reading these papers, to see the number of times the "third harmonic" was referred to or discussed. There are a great many phenomena existing in engineering which are not generally observed until something happens to make them annoying in practical work.

In certain transformer connections the third harmonic, inherently in the magnetizing current with applied sine wave voltage, is the cause of abnormal stress to ground. This is especially so with long lines of high capacity.

If Y-connected auto-transformers, with their neutral grounded as the only ground, are used to step up the generator voltage, *abnormal potentials to ground* may result. These excess voltages are *not indicated by a voltmeter, but by "static" on leads*, excessive losses, or *by a spark gap* connected between one line and ground. The reason that a voltmeter does not indicate this high voltage is that the effective value of the voltage is not greatly changed, but only the maximum value of the wave is increased, and this is indicated by a spark gap, or stress between the insulation and ground. The cause of the voltage distortion is as follows:

When a sine wave e.m.f. is applied to a transformer, the resulting magnetizing current wave cannot be a sine wave but must follow the changing permeability of the iron,—this current wave contains the third harmonic. The current and voltage waves can never be the same, but, if the magnetizing current wave is a sine wave, the voltage wave must then contain a third harmonic, or *vice versa*. Hence, if anything prevents or suppresses the third harmonic in the magnetizing current the applied sine wave of voltage must then become distorted.

In a three-phase transformer the currents are 120 deg. apart for the fundamental frequency, or 3 × 120 or 360 deg. apart for the third harmonic; that is, in phase. Thus for Y-connected auto-transformers the triple-frequency magnetizing currents to neutral must be in phase. The sum of the three currents flowing to a point must be zero. Hence, as the third harmonic magnetizing currents are all in phase, they must all be zero to satisfy these conditions; that is, they must be suppressed. This means that the current wave approaches a sine and that therefore the voltage to neutral cannot be a sine wave but must be peaked, or contain the third harmonic, which appears as voltage rise to neutral and causes extra iron and insulation loss. The distortion does not appear in the voltage between lines because

the distortion between one line and neutral is cancelled by that of the other two lines. The voltage distortion may be eliminated by supplying a path for the triple-frequency exciting current; that is, in this case, by connecting the transformer neutral to the generator neutral. This supplies a single-phase circuit for the triple frequency through the line and generator. A current of the proper phase relation flows and the distortion disappears.

If, before this connection is made to the generator, the transformer is connected to a transmission line, a path is supplied for triple-frequency current through the capacity from line to ground. This capacity offers three single-phase circuits. A triple-frequency current thus flows but it has not the proper phase relation for the triple-frequency excitation current, and instead of eliminating the voltage distortion it greatly increases it. A double peak may occur in the fundamental voltage wave which causes an increased iron loss. This distortion, however, also generally disappears when the auto-transformer neutral is connected to the generator neutral. Without this inter-connection the distortion is greater in the case where the transformer is connected to a capacity. The peak of the wave may be several times normal. The effect of capacity is well brought out by Mr. Blume. There are other ways of supplying this third-harmonic current; for instance, by a closed delta in the transformer.

If a grounded-Y auto-transformer is used to step up the voltage of a generator with non-grounded neutral, and at the far end of the line is a transformer with grounded Y on the line side and delta on the low side, triple-frequency current is supplied from this transformer to the auto-transformer through the ground by the three single-phase paths. These ground currents may cause telephone troubles; if the transformer at the far end is small compared to the auto-transformer, the triple-frequency exciting current may overload it and cause it to burn out.

The third harmonic is thus a "constant current" effect, that is, the voltage drops when triple-frequency current with the *proper phase relation flows* through a low-resistance path. If the circuit has high resistance the voltage becomes high.

There may also be a third harmonic in the generator wave, due to the relation of the windings, which has a "constant voltage" effect and which may produce very *heavy triple-frequency currents* with improper connection, or when a short circuit path is afforded for these currents. Precautions are thus necessary where several generators are connected in parallel and the neutrals grounded. If all of the generators are of identical design, very large triple-frequency excitation currents may flow unless the field excitation is the same on all of the generators. If the generators are not of identical design, dangerously large triple-frequency currents may result. When a number of generators are operated in parallel and the voltage is stepped up by auto-transformers, it is often practicable to ground only one generator

at a time and to connect to this ground all of the transformer neutrals.

Whenever auto-transformers are used it is necessary to investigate the possibilities of trouble for the particular case under consideration. Their use is generally not to be recommended.

There are other transformer connections which may cause high triple-frequency voltages, as an instance, Y-Y.

Louis F. Blume: In connection with Mr. Clinker's paper, I wish to point out that the Scott-connected transformer should not be held responsible for the third harmonic which appears in the three-phase system. If the Scott-connected transformer had been omitted, and the generator connected in "T", the third harmonic would have appeared in the line just as described.

F. C. Green: Reference is made in the paper by Messrs. Sorensen and Newton to some experiences that were had in a western system. I happened to be connected with the installation of that system, and made some tests on triple-frequency effects related by the authors in their paper.

For the tests, the bank of compensators was excited at 60,000 volts and stepped this voltage down to 50,000 volts. The neutral was not grounded except for the slight grounding effect that resulted when measuring potential between neutral and ground by means of a potential transformer. Tests were made with the auto-transformers open on the 50,000-volt side and also with them feeding into the 50,000-volt system, there being practically no difference in the measured values for the different conditions. With 60,000 volts impressed, the voltage between neutral and 60,000-volt terminals was 42,000 volts; between neutral and ground, 18,600 volts; between 60,000-volt terminals and ground 36,600 volts. All measurements were made with potential transformer. No tests were made under the condition that had caused trouble, namely, with only the auto-transformer neutral grounded in the 50,000-volt system; the reason being fear of damage to the line.

Under the system of connections that was planned to be used there, the grounding of the neutral would not have caused any excessive voltages. On occasions of line disturbances, it sometimes happened that all other grounded neutrals in the system were disconnected, leaving only the auto-transformers' neutrals grounded.

Mr. Clinker mentions in his paper an instance where trouble due to triple-frequency effect was relieved by grounding the auto-transformer neutral. In the system discussed above, it was necessary to unground the neutral to prevent damage. The theory for this case is given in Mr. Blume's paper.

Triple-frequency effects have been well covered and there is now no reason for experiencing any more trouble from them. Until some new phenomena develop in operation, due to their existence, it seems that efforts should be directed to the solution of other and more vital features of the subject under discussion.

C. L. Fortescue: In connection with Mr. Clinker's paper, if I am not mistaken, in previous discussions on a paper by Mr. Frank this peculiarity of the Scott connection has been pointed out. The third harmonics which exist in the two-phase generator are transformed, so that they appear in the three-phase circuit in three-phase relation after transformation. This will be found to be true also in any transformation or any generation, whether produced in a generator or transformed in a transformer in which there is dissymmetry in the phases. The triple harmonic effects present will appear in three-phase relation, causing differences in the wave forms of the voltages between the mains as a result of dissymmetry in the windings of the transformers or in phases of the generator.

P. M. Lincoln: This observation brought out in Mr. Clinker's paper is of interest to me, because in studying the wave forms of the Niagara Falls generator, which was installed about nineteen years ago, I observed the same thing. The Niagara generators had slightly flat-topped waves, similar to those Mr. Clinker has shown. If you take a two-phase generator, such as we had at Niagara, and get three phases from it by the Scott connection, you will have one of the phases going through the transformation with the wave form unchanged, the same on the three-phase as on the two-phase side. That will be what we may call the main phase. Of the other two, one of them will be a peaked wave and the deformation will be to one side of the neutral axis, say on the right-hand side. You will find the other phase will be exactly similar, except that the peak will be formed on the left-hand side. If you start with a peak wave, you will find when you get through to the three-phase side, you will have one peak wave and two flat-top waves, distorted, one to the right and the other to the left. It is not a new observation, by any means, and has been known for a great many years.

J. M. Weed: I wish only to raise a point of theoretical interest in connection with Mr. Clinker's paper. Mr. Clinker has attributed the third-harmonic component in exciting currents to the effect of hysteresis. To see that this is not correct, it is only necessary to consider that hysteresis constitutes an energy loss in the iron, and that with a sinusoidal voltage applied, energy can be supplied only by current of the same frequency as the voltage, *i.e.*, by a fundamental component of the exciting current. The triple harmonic and all higher harmonic components of the exciting current are not due to hysteresis, but to the permeability characteristics of the iron; *i.e.*, to variations in permeability with changes in the magnetic density.

D. C. Jackson: As Dr. Kennelly referred to the artificial line at the Massachusetts Institute of Technology, it will be interesting to add that it is a line made up of No. 12 B. & S. gage wire that has resistance, self-inductance and capacity which causes it to represent substantially 750 miles of length of line, 500,000-circular-mil conductor, spaced at 8 feet, center to center.

That is about the line which would be used for the transmission of power from the Falls of the Nile to South Africa.

The one-third length which Dr. Kennelly used in his experiments was a part of that line. The reason for the line being built of the No. 12 B. & S. gage wire was to make it practicable to use ordinary portable ampere-meters, voltmeters, or wattmeters in connection with it, without interfering seriously with its normal performance. As far as tests have gone, that seems to be what can be done, and makes it very convenient. One can find out the operating characteristics of the line by using portable ampere-meters, voltmeters or wattmeters, in the ordinary fashion, apparently, and do it in relatively little time. I think, in the case of the Schenectady line, it is necessary to have special instruments to be used with the experimental line, it being of small wire of relatively high resistance.

This line at the Massachusetts Institute of Technology when operated at 60 cycles, open circuit, pure sine wave, gives a rise of voltage of about 9 to 1 in the full length, that is, 120 volts impressed at the generator end gives something over 1000 volts at the receiver end, open circuit. Of course, a very small load on the line changes that promptly, as the formula shows.

The line responds closely to what the formula indicates, although it is what is called a lumpy line.

Presented at the 296th Meeting of the American Institute of Electrical Engineers, Pittsfield, Mass., May 29, 1914.

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INFLUENCE OF TRANSFORMER CONNECTIONS ON OPERATION

BY LOUIS F. BLUME

ABSTRACT OF PAPER

In this paper the relative advantages and disadvantages in operation of the more important three-phase transformer connections are discussed. Three conditions of operation are given: First, normal; second, operation of a bank with one phase disabled; third, effect of line grounds on operation.

The paper is not complete, particularly in that high-frequency or switching phenomena are not discussed. Its major purpose is to give a fairly adequate presentation of insulation stresses at relatively low frequencies to which transformers are subject in either normal or abnormal conditions of operation. These frequencies include the fundamental or generated frequency and its harmonics and the natural frequency of the system.

The behavior of three-phase auto-transformers under the various conditions of operation given above is also analyzed.

TRANSFORMERS for use on three-phase systems are in the majority of cases connected either delta-delta or delta-Y, these two being almost universally considered superior to the few other connections which may be used for three-phase transmission. Opinions differ, however, as to their relative merits, and the purpose of this discussion is to analyze some of the factors involved.

Operation in Case of the Disabling of One Phase. In the delta-delta connection, operation can be continued by running open delta after removing the disabled phase, under which condition the bank can handle 58 per cent of its original capacity. When, however, there are two or more delta-delta banks operating in parallel, the advantage of open delta operation of one bank becomes less, on account of the fact that a mutual relation exists between the loads in the two banks. For example, if one phase of one bank is removed, instead of being able to operate the good bank at 100 per cent capacity and the open delta bank at 58 per cent capacity, making a total of 158 per cent (assuming all transformers alike and that 200 per cent was the original

total capacity of the two banks) it will only be possible to derive from the five transformers 133 per cent capacity.[1] When two delta-delta banks are operated in parallel with one open delta bank, a total capacity of 233 per cent instead of 258 per cent is obtainable. Thus it is evident that with increasing numbers of delta-delta banks connected in parallel, the advantage of being able to operate any one of them in open delta decreases. This, however, is not a serious objection, because, by placing the proper amount of reactance in series with the weakened phase, its available capacity can be considerably increased.

Open delta operation of a three-phase core type transformer is, in the majority of practical cases, not possible, on account of the interlinked magnetic structure.

In delta-Y connections, the disabling of one phase renders the whole bank inoperative, except in the case when it is possible to change the voltage of the line connected to the Y side of the transformers. This is feasible if a line transmits power from one bank of delta-Y transformers at one end to another bank of Y-delta transformers at the other end, and operation can be continued in case of the disability of one phase by changing the Y connection to open delta in both step-up and step-down transformers, thus reducing the transmission line voltage to 58 per cent of its original value. Under this condition the capacity of the transmission line and transformers is reduced to 58 per cent of the original value, which is equal to the capacity obtained in the case of operating one delta-delta transformer bank in open delta. When, however, two or more Y-delta banks are operated in parallel, the disability of one phase renders the whole of one bank inoperative.

The Effect of Differences in Characteristics of the Transformers Making up a Transformer Bank. When transformers of slightly different ratios are connected in delta-delta, large circulating currents will result in the delta circuits, depending upon the amount of off ratio and the impedance of the transformers; and when transformers having different impedances are connected for delta-delta operation, the division of load between them will be very unequal. In general, a delta-delta connection is very sensitive to variations in impedances and ratios. A Y-delta bank of transformers is far less sensitive to such variations, and in fact transformers having considerable differ-

1. See article entitled "Delta-Delta Transformer Banks in Multiple," by W. W. Lewis, *General Electric Review*, January, 1912, page 47.

ences in ratio and impedances can be used to make up a Y-delta bank without appreciably affecting the current or voltage division of the phases. From this it is evident that, in cases where a three-phase bank is to be made up of dissimilar units of equal kilovolt-ampere capacity, more satisfactory operation can be obtained by connecting delta-Y than delta-delta. On the other hand, if the kilovolt-ampere capacities of the units are different, the delta-delta connection will probably result in a greater combined capacity than Y-delta, because in the delta-delta banks the currents will divide to a certain extent, at least in proportion to the kilovolt-ampere capacity of the units, whereas in the Y-delta connection the currents in all three phases are equal.

Insulation Stresses

The potential stresses on the insulation at fundamental frequency are worthy of consideration and become particularly important in high-voltage transformers. Under normal conditions of operation, that is, when the connected line is free from grounds, the maximum value of these stresses is equal to 58 per cent of line potential. In the delta connection the minimum value of the insulation stress is equal to 29 per cent and occurs at the middle point of the winding, whereas in the Y connection the stress is zero at the neutral end of the winding, and increases uniformly to its maximum value of 58 per cent at the line end. These stresses are tabulated below for convenience in comparison, together with corresponding insulation safety factors, the latter being based on the assumption that the windings are insulated to withstand a test equal to twice normal voltage.

TABLE I

Insulation Stresses from High-Voltage Winding to Ground, in Three-Phase Connections, at Fundamental Frequency, under Normal Operating Conditions.

	Stresses in per cent of line voltage			Safety Factor		
	maximum	minimum	average	maximum	minimum	average
delta	57.7	28.8	43.2	7	3.46	4.64
Y	57.7	0	28.8	infinity	3.46	7

When one terminal of the transformer is grounded, these stresses are all materially increased. Their values at various portions of the winding are shown in Fig. 1. Here high-potential stresses in the insulation from winding to core in per cent

of the normal line voltage for every portion of the high-voltage winding are plotted as ordinates. The curve shows that the stress in the insulation of delta winding is practically equal to line voltage at all points of the winding, the voltage at the middle point, however, being reduced to 87 per cent of this value. On the other hand, in the Y connection the stress in the winding is graded, being a minimum at the neutral and a maximum at the line end. Three cases are given: Curve *a* shows the condition when the neutral is not grounded; curve *b* shows the condition when the neutral is grounded, and when the line is capable of maintaining normal voltage notwithstanding the short circuit produced by a ground on the line; and curve *c* shows the stresses in delta-Y transformers excited on the delta side and operating with a grounded neutral. A particularly large reduction of stress is obtained in the latter case, the maximum never exceeding 58 per cent of line potential. These stresses, together with their corresponding safety factors, are given in Table II.

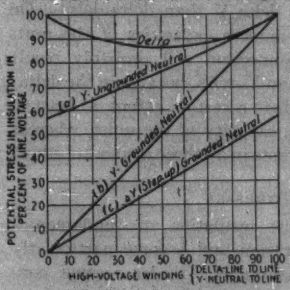


FIG. 1—EFFECT OF GROUNDS ON POTENTIAL STRESSES AT FUNDAMENTAL FREQUENCY ON THREE-PHASE CONNECTIONS

TABLE II

INSULATION STRESSES FROM HIGH-VOLTAGE WINDING TO GROUND, IN THREE-PHASE CONNECTIONS, AT FUNDAMENTAL FREQUENCY, WITH ONE TERMINAL GROUNDED.

	Stresses in per cent of normal voltage			Safety factor		
	minimum	maximum	average	maximum	minimum	average
delta	86.6	100.	93.3	2.3	2	2.1
Y (a)	57.7	100.	78.8	3.46	2	2.54
Y (b)	0	100	50	infinity	2	4
Y (c)	0	7.7	28.8	*	3.46	7

Although the above stresses are relatively small and on that account probably never immediate causes of breakdown, nevertheless it should be borne in mind that stresses of higher frequency are superimposed upon these. It therefore follows that with the transformer connection possessing the smallest average insulation stress at fundamental frequency, or conversely, that

connection which possesses the maximum insulation safety factor (when fundamental stresses only are considered), a greater margin is available for withstanding stresses at higher frequencies. These margins, which are obtained by subtracting the insulation stresses given in Tables I and II from the transformer test voltage (200 per cent of normal voltage), are given in Tables III and IV.

TABLE III

INSULATION MARGINS FOR NORMAL OPERATIONS, IN PER CENT OF LINE VOLTAGE.

	maximum	minimum
delta	171 per cent	142.3 per cent
Y	200	142.3

TABLE IV

INSULATION MARGINS WITH ONE TERMINAL GROUNDED, IN PER CENT OF LINE VOLTAGE.

	maximum	minimum
delta	113 per cent	100 per cent
Y (a)	142	100
Y (b)	200	100
Y (c)	200	142

These tables, however, only roughly indicate that the Y connections, particularly in the case represented by curve *c* of Fig. 1, are capable of withstanding greater stresses at higher frequencies than the delta connection; it would be a true indication provided the insulation is only capable of withstanding twice the line voltage. The table should therefore have been worked out in terms of the actual strength of the insulation instead of the test voltage for which it was designed.

Line Grounds on Isolated Systems. In an isolated system, when a solid ground occurs on the line, the grounded wire is reduced to zero potential and the potentials of the other lines are raised to line potential above ground. If a ground occurs on the line, a considerable distance from the transformers, the charging current flowing through the reactance of the line will cause the potential of the grounded line at the transformer to be somewhat above zero, and since the induced voltage of the transformer will also be somewhat greater than its normal value on account of the reactance drop caused by the charging current (particularly when the transformer possesses high inherent reactance), the free line is raised to a fair percentage above its normal potential above ground. This effect is also somewhat larger than one

would ordinarily assume, on account of the fact that the electrostatic capacity of a transmission line having one of its lines solidly grounded is in the majority of cases considerably greater than when the lines are thoroughly insulated. However, none of these effects is very large, and in general the result of a dead

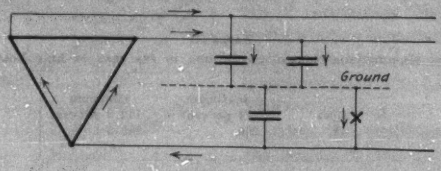


FIG. 2

ground on an isolated system is to bring the other two wires to a potential somewhat greater than normal above ground. The insulation safety factor has thereby been reduced to a value slightly less than two, and it is evident that the values of insulation stresses and safety factors given in Tables I and II and the curves in Fig. 1, are not quite correct when transformers are connected

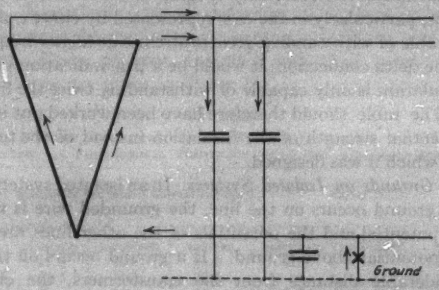


FIG. 3

to transmission lines of considerable electrostatic capacity. It is possible to operate an isolated system with one of its lines solidly grounded without serious risk, and there have been cases of high-voltage, long-distance transmission lines operating in this manner for several hours with a solidly grounded or even a broken line.

But when the ground occurring on the line is not a dead ground, an arc results between line and ground which, on account of the fact that it is in series with the electrostatic capacity of the transmission line (see Fig. 2), generally results in an unstable arc or an arcing ground.

General experience with arcing grounds on isolated systems has shown that they are usually accompanied by large rises in potential of transmission line and connected transformers. This rise in potential is shown diagrammatically in Fig. 3.

Such conclusions are corroborated also by the results obtained in the experiments made by Dr. E. J. Berg, and reported in an Institute paper[2] in June, 1908, entitled *Tests with Arcing Grounds and Connections*.

Grounds on a System Having Neutral Grounded. A ground on a system having a neutral grounded, results in a short

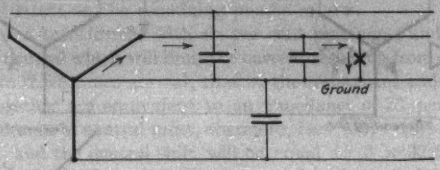


FIG. 4

circuit, and a dynamic current flows, the value of which depends upon the combined impedance of the circuit through ground and impedance of the transmission line and connected apparatus through which the short circuit flows. (See Fig. 4). This results in an impedance drop throughout the circuit and a consequent lowering of the voltage. The resultant arc is in series with the reactance of the transmission line, and since reactance tends to stabilize an arc, the likelihood of an arcing ground resulting is therefore much more remote than in the case of the isolated system.

In general, with the grounded Y system, resonance on account of the electrostatic capacity of the line is not likely, since the line capacity is not in series with line grounds. There is one particular case, however, when resonance may be produced. For example, in a delta-Y system with grounded neutral, suppose

2. TRANSACTIONS A. I. E. E., 1908, XXVII, Part I, page 741.

one phase on the delta side is burned open, resulting in open delta excitation. The high-voltage side of the burned-out phase then constitutes a reactance in series with electrostatic capacity of the transmission line and excited by the voltages from the other two phases. If the charging current of the transmission line is equal to the magnetizing current of the transformer, resonance is established at fundamental frequency. However, the increase in voltage is limited by the saturation of the transformer; for example, assuming that the normal flux density of the transformer is 80,000 lines per sq. in. (6.452 sq. cm.), it follows that more than a 50 per cent increase in voltage can hardly be expected. The resulting stresses on the insulation are therefore less than those reached in isolated systems when grounds occur on the line.

If the voltage impressed on the low-voltage side contains a

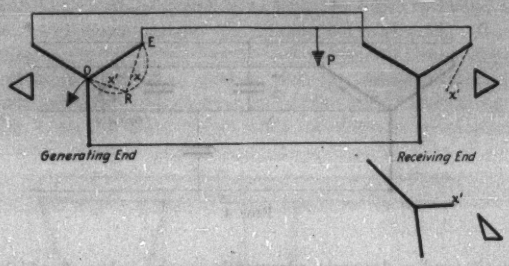


FIG. 5

prominent fifth harmonic, there is a probability of establishing resonance at five times normal frequency, and dangerous voltages built up thereby. However, the likelihood of obtaining resonant conditions at five times normal frequency is not very great, and moreover the fifth harmonic in impressed voltage is generally small. Also the importance of this consideration is small on account of the fact that it can only take place when one delta bank is connected to the transmission line and when one phase of the low-voltage delta becomes open-circuited.

The effect, upon the distribution of the voltage, of a line ground on a grounded Y system, is shown diagrammatically in Fig. 5. The portion consumed by line resistance and reactance brings the potential of P to some point X' and the potential OX' is consumed in overcoming the resistance of the current path from the line ground P to neutral O.

The worst short circuit occurs when a dead ground happens on the line near transformer A, which causes a collapse of the short-circuited phase throughout the system, and a short-circuit current only limited by transformer reactance.

Resistance in Neutral. To reduce the value of this short-circuit current, resistances are often inserted between the neutral point and ground.

A resistance inserted in the neutral causes the neutral o to shift with respect to ground when a ground occurs on the line, or relatively speaking, the ground will shift along the line OX'. If resistance of ground is small compared to resistance at neutral the ground potential in Fig. 5 is X'. A dead ground on the line near the transformers causes the neutral to shift a value equal to $\frac{rE}{r+jx}$, where r equals resistance of neutral and x equals reactance of transformer. It is evident that an increase in potential stress on the remaining phases results.

Assume a transformer with six per cent reactance, and resistance of neutral which will limit the current resulting from a dead ground to three times normal, that is, the resistances and reactances together are equivalent to an impedance of 33 per cent. The reactance of neutral must, therefore, be $\sqrt{(33)^2-(6)^2} = 32.5$ per cent, and the neutral shift will be equal to $3 \times 32.5 = 97$ per cent. *Evidently any resistance inserted in the neutral, if it is to limit currents to values appreciably less than those obtained when the neutral is dead grounded, must be capable of withstanding practically normal phase potential.* Moreover, the purpose of grounding the neutral is destroyed, for a neutral shift of 75 per cent or more of the phase voltage means that the free lines have been raised to practically full line potential above ground.

A neutral will therefore remain stable only when the IR drop produced across the neutral resistance by the short-circuit current is small compared with the line voltage. Practically all the voltage must be consumed by the resistance of the ground and resistance of neutral in series. From this we can conclude that *a neutral with resistance will hold the neutral fairly steady and prevent undue rises in potential, provided the line grounds do not occur with resistance* (including line resistance to point of ground) *less than ten times the resistance in the neutral.*

The ratings of the resistance inserted in the neutral for various limiting values of short-circuit current are given in Table V. These are worked out on the basis of transformer reactance

equal to six per cent, resistance one per cent, and on the assumption that the short-circuit current is limited only by the resistance in the neutral and the impedance of the transformers.

TABLE V

Short-circuit current	Volts across neutral in per cent of transformer normal voltage	Rating of kv-a. resistance in per cent of normal kv-a. of one phase
16.4 times normal	0	0
12 " "	57	644
10 " "	70	700
5 " "	90	450
3 " "	94	280
2 " "	98	196
1 " "	100	100
0.5 " "	100	50

The size of the resistance will also depend upon the length of time short circuit is maintained. For example, if the system is protected by relays which disconnect the apparatus in two minutes, the resistance must be designed to dissipate the power given in the table for this period of time.

Grounding the Neutral at Receiving End. In the preceding discussion the neutral at the generating station was in every case considered grounded. However, when the neutral of the step-down transformers at the far end of the transmission line is grounded, and the neutral at the generating station isolated, a different condition exists. In this case, when one line near the step-down transformers becomes grounded, one phase is short-circuited thereby, and current flows as indicated by the arrows in Fig. 6. If the step-down transformers are small compared with the kilovolt-ampere capacity of the system to which they are connected, the line voltage is not appreciably affected by this short circuit, although the grounded line assumes ground potential. Line potential is therefore impressed across two phases, as indicated in *a* of Fig. 6, and the ungrounded lines assume a potential of practically line voltage above ground. The currents flowing are single-phase and produce in each phase a reactance drop equal to *ab*, that is, phase voltage.

If, on the other hand, the step-down transformers have a kilovolt-ampere rating comparable with the rating of the transformers at the generating station, the resulting short-circuit currents are severe enough to reduce the line potential at the step-down transformers very materially. On that account

they are not as liable to an increase in induced potentials and potential stresses from winding to ground.

Complete protection, however, is not given in this case to the step-up transformers, for if a ground occurs near the generating station, the short-circuit currents must flow through the ground between the generating station and receiving end, in which case the voltage drop on the ground and in lines may be sufficient to limit the short-circuit currents, and therefore decrease the reactance drop within the transformers. Under this condition, the terminals of the step-up transformers will assume a potential above ground equal to line voltage.

Auto-Transformers. Wherever it is desired to interconnect two high-voltage systems of not very great voltage difference,

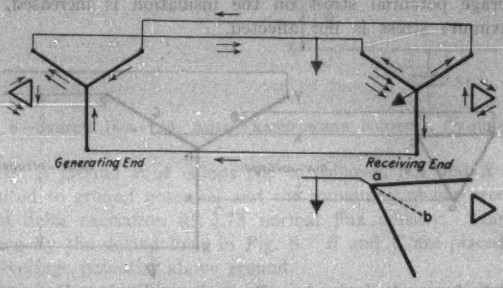


FIG. 6

as, for example, 100,000 volts and 60,000 volts, the use of Y-connected auto-transformers is cheaper than transformers, because a large saving is effected due to the fact that the rating is only a fraction of the power which the auto-transformer can transmit from one system to the other. Since reduction in rating is only material when the connection is Y, a delta-connected auto-transformer is seldom used. But when the transformation ratio is three or more, the saving in the use of auto-transformers instead of transformers is too small to outweigh the disadvantages which their use entails.

As auto-transformers are cheaper from the standpoint of first cost, it is of interest to investigate potential stresses at normal or fundamental frequency resulting from abnormal conditions, as line grounds, etc., in order to determine their

reliability and therefore their eventual cost. These insulation stresses depend upon whether the system is isolated or grounded Y, and whether the neutral of the auto-transformer is grounded. There are four cases:

Case I. System Isolated, Auto-Transformer Neutral Ungrounded (See Fig. 7)

(a) A triple-frequency e.m.f. exists from line to neutral, increasing the induced potential stress from 20 to 50 per cent, depending upon the flux density in the iron. The insulation stress from winding to core is increased at the neutral, but not at the line ends of the winding. The presence of the triple-frequency voltage, therefore, is not serious, for although the average potential stress on the insulation is increased, the maximum stress is not affected.

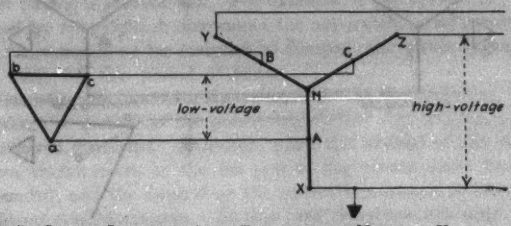


Fig. 7—System Isolated, Auto-Transformer Neutral Ungrounded

(b) A ground at X (Fig. 7) places the low-voltage lines B and C at a potential above ground approximately equal to 0.58 high-voltage + 0.42 low-voltage.

Thus, if the auto-transformer steps up from 60,000 volts to 100,000 volts, a solid ground existing on the high-voltage line raises the potential of the low-voltage line to 81,000 volts above ground.

Case II. System Isolated, Auto-Transformer Neutral Grounded (Fig. 8)

(a) The triple-frequency e.m.f. which is present as in Case I, is now exerted across the line insulation to ground. This is particularly dangerous if the auto-transformer is connected to systems having considerable electrostatic capacity. Electrostatic capacity between lines and ground causes a charging

current in which the third harmonic is prominent, which reacts on the triple-frequency e.m.f., intensifying it. Potential peaks equal to three times normal can easily be obtained in this way at ordinary densities, although at very low densities and at saturation densities, the danger is less. The charging current necessary to produce these voltages is not large.

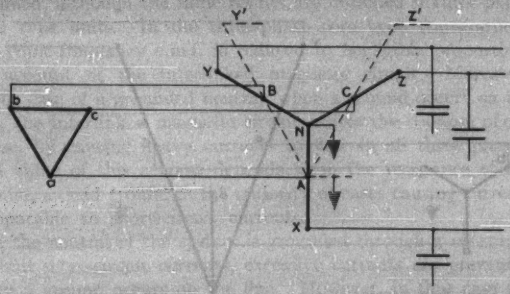


FIG. 8—SYSTEM ISOLATED, AUTO-TRANSFORMER NEUTRAL GROUNDED.

(b) A ground at A causes NA to collapse, NA and X are reduced to ground potential and the remaining phases receive open delta excitation at 1.73 normal flux density. This is shown by the dotted lines in Fig. 8. B and C are placed at low-voltage potential above ground.

(c) A ground at X produces the same result as a ground at A.

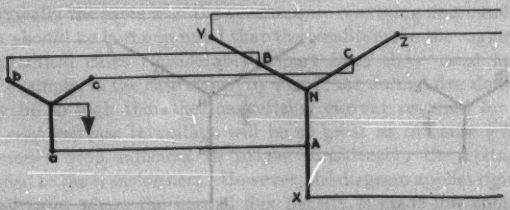


FIG. 9—SYSTEM GROUNDED, AUTO-TRANSFORMER NEUTRAL UNGROUNDED

CASE III. SYSTEM NEUTRAL GROUNDED, AUTO-TRANSFORMER NEUTRAL ISOLATED (SEE FIGS. 9 AND 10)

(a) Triple-frequency voltage present as in Case I. Since the neutral is isolated, there is no danger of the triple-frequency voltage being intensified.

(b) A ground at A short-circuits one phase of the low-voltage system.

(c) A ground at X results in distortion of and increase in induced voltage in the auto-transformers, as shown in Fig. 10. The low-voltage system does not receive an abnormal voltage or abnormal insulation stress.

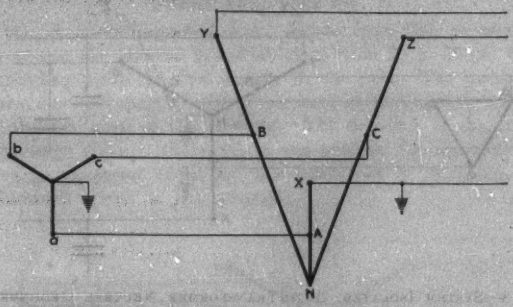


FIG. 10—SYSTEM GROUNDED, AUTO-TRANSFORMER UNGROUNDED, SHOWING EFFECT OF DEAD GROUND OCCURRING ON LINE

CASE IV. SYSTEM NEUTRAL GROUNDED, AUTO-TRANSFORMER NEUTRAL GROUNDED (SEE FIG. 11)

(a) Triple-frequency e.m.f. is much reduced because triple-frequency currents can flow through ground connections. The

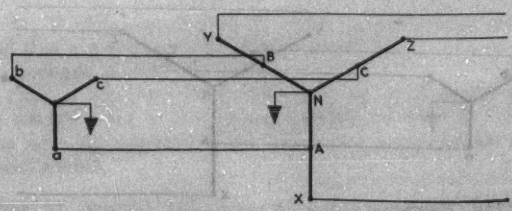


FIG. 11—SYSTEM GROUNDED, AUTO-TRANSFORMER NEUTRAL GROUNDED.

reduction in triple-frequency e.m.f. depends somewhat upon the resistance of the ground circuit.

(b) A ground at A short-circuits one phase of the low-voltage circuit.

(c) A ground at X short-circuits one phase of the auto-transformer and one phase of the low-voltage circuit through the auto-transformer reactance. The potential of B and C cannot rise above normal values.

In the above cases, single-phase auto-transformers were assumed, although the same results are obtained in three-phase shell type units. In the three-phase core type transformers, the triple-frequency e.m.f. is reduced to negligible proportions on account of the interlinked magnetic circuit. Moreover, in the case of a grounded neutral, when a ground occurs on the line, the interlinked magnetic circuit resists the collapse of one phase, by causing heavy currents to flow in all three phases. The value of this current depends upon the resistance of the ground, a dead ground in the majority of cases causing currents comparable to short-circuit currents.

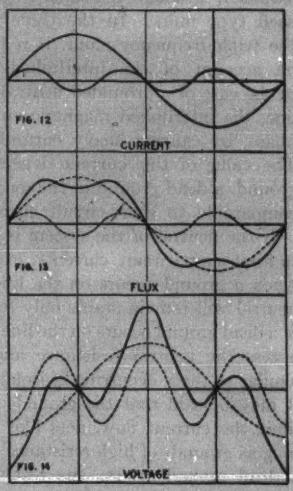
If the neutral of the system is grounded through a resistance to limit short-circuit currents, excessive currents are prevented when a ground occurs on the line. However, in that case the neutral will remain stable only for high-resistance line grounds. If a dead ground occurs on the line, full phase voltage is impressed across the neutral resistance and potential stresses will exist similar to those occurring in isolated delta systems. In general, it may be said that the grounded neutral, with a resistance to limit the current flow, acts like a solidly grounded system as long as grounds of high resistance only occur on the line. When a dead ground occurs, the resulting potential stresses will be practically the same as if the system were operating ungrounded.

It should be borne in mind that the conditions in the majority of practical cases considerably depart from those cited here. For example, in the case shown by Fig. 7, the normal flux density may be so high that the magnetizing current required for 73 per cent increase in voltage will be so great as to cause a line reactance drop sufficient to reduce considerably the voltages applied to the transformers. However, the diagram applies rigidly to all cases where the normal flux density is made low enough so that, when a ground occurs, the cores will not be supersaturated. Similarly, the conditions shown by Fig. 10 will not occur in practise on account of the excessive magnetizing currents resulting.

It is evident from the analysis of the four cases given above, that high-voltage auto-transformers should not be generally used

without solidly grounding the neutrals. Grounding the neutral necessitates the elimination of the triple-frequency e.m.f., which may be done either by using the three-phase core type structure or by having a Y-delta transformer with grounded neutral connected to the same system. The latter method, is, however, questionable, because the safety of the auto-transformer then depends upon proper operation of another piece of apparatus.

If such precautions are taken, auto-transformers should operate successfully, although they still possess the objection that the high-voltage and low-voltage systems are rigidly connected together by means of an electrical conductor, whereas a transformer connects the systems in a more flexible manner, *i.e.*, magnetically. Due to this, a disturbance occurring on one line is likely to be felt on the other, when auto-transformers are used. With tie-in transformers, operating on isolated systems, it is possible for grounds to occur on line without disturbing the operation or increasing the stresses on the other lines.



FIGS. 12, 13, 14—CURRENT, FLUX AND VOLTAGE RELATIONS IN Y-CONNECTED AUTO-TRANSFORMERS

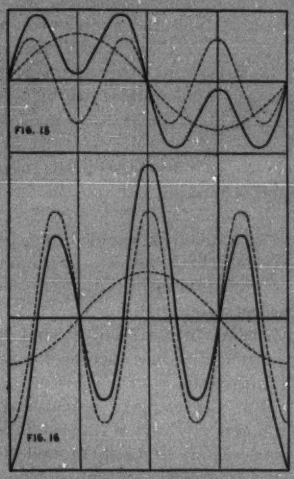
THE THIRD HARMONIC IN THE Y CONNECTION

Due to the fact that the permeability of iron decreases as the flux density increases, the wave shape of magnetizing current in a transformer is different from the wave shape of the electromotive force. When the impressed electromotive force is a sine wave, the magnetizing current shows a peak, which, when analyzed, resolves itself into a prominent third harmonic and higher harmonics of lesser values.

In the Y connection, third-harmonic currents and currents having frequencies multiples of the third cannot flow, on account of the fact that these currents in the three phases would be in

phase with each other, and to permit them to flow, a circuit must be provided at the neutral.

Owing to the fact that the triple harmonic current necessary for sinusoidal excitation cannot flow in Y-connected transformers the resulting flux wave takes a flattened form, which, when analyzed, resolves itself into the fundamental and a triple harmonic. The flux wave under this condition is shown in Fig. 13, and the corresponding voltages induced from line to neutral are given in Fig. 14. For average operating densities in transformers, the triple-harmonic voltage is approximately 60 per cent of fundamental voltage.



FIGS. 15, 16.—ANALYSIS OF THIRD HARMONIC INTENSIFICATION IN Y AUTO-TRANSFORMERS

When the neutral of the auto-transformer is grounded, the triple harmonic together with the fundamental is impressed between line and ground across the capacity of the connected transmission line. A triple-frequency charging current flows into the line and through the auto-transformer windings. The phase angle of this current with reference to the fundamental magnetizing current is shown in Fig. 12. This triple-frequency current constitutes an additional magnetizing current in the auto-transformer, and a comparison with Fig. 13 shows that it is in phase with the triple-frequency flux which was produced by the original sine wave magnetizing current. Therefore the triple-frequency current acts to increase the triple-frequency flux and a corresponding intensification of triple voltage ensues. The increased triple-harmonic voltage results in a greater triple current, which causes a further increase in flux. This intensification is only limited by the saturation of the transformer. Figs. 15 and 16 show flux and voltage waves in which the third harmonic has reached its maximum value. It is evident that under such conditions of operation the core loss of the transformers will

be about three times normal and the insulation stress about four times normal.

Conclusions

The following are the more important conclusions which may be drawn from this paper:

First: Isolated systems are subject to greater insulation stresses than grounded systems.

Second: In grounded systems, the average insulation factor of safety is greater than in isolated systems under similar conditions of operation.

Third: In isolated systems, the stresses at lower frequencies under certain conditions, may reach values sufficiently high to injure or destroy the transformer and other apparatus connected to the system.

Fourth: In an isolated system, a ground on the line is more likely to result in an arcing ground or intermittent arcs than in a grounded system.

Fifth: A ground on the line in a solidly grounded system, reduces the potential of the system with respect to ground, whereas in the isolated system, a ground on the line increases the potential of the system with respect to ground.

Sixth: A resistance inserted between neutral and ground to limit the value of short-circuit current increases thereby the insulation stresses resulting from line grounds.

Seventh: If it is desired to limit the value of potential at fundamental frequency above ground of any part of the system to 57 per cent of line potential, it is necessary to solidly ground the neutrals at both receiving and generating ends of transmission line.

Eighth: If receiving transformers of relatively small kilovolt-ampere capacity are connected with grounded neutral to an otherwise isolated system, they are liable to severe short circuits, and the grounded neutral only partially protects the system from potential rises.

Ninth: In Y-connected auto-transformers, it is dangerous to operate with isolated neutral except when the ratio of transformation is nearly unity.

Tenth: In Y-connected auto-transformers, it is dangerous to operate with isolated neutral except when the entire system is isolated.

Eleventh: In Y-connected auto-transformers, it is dangerous to operate with grounded neutral unless the triple-harmonic voltage between line and neutral is eliminated or kept negligibly small.

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A STUDY OF SOME THREE-PHASE SYSTEMS

BY CHARLES FORTESCUE

Abstract of Paper

The star-star, delta-delta, delta-star and star-delta connections are taken up in order and their individual peculiarities and characteristics, precautions that must be taken in operation to avoid trouble, and where and when the system may be grounded with best results, are discussed.

The question of delta-delta vs. delta-star is considered:

(1) For moderate voltages the delta-delta system has the advantage on account of its greater flexibility.

(2) For high voltages the delta-star connection is preferable, chiefly on account of its greater strength and lower cost. There is a probability that a delta-star bank of transformers will cause less disturbance in switching than one that is delta-delta connected.

(3) There are much greater possibilities of development in transformers designed for delta-star connection than for any other.

(4) Past and present practise upholds the use of the delta-star connection in preference to the delta-delta for high-voltage transmission.

IT IS proposed in this paper to study several common methods of connecting transformers for use on polyphase systems, with the view of displaying the advantages and disadvantages of each, showing under what conditions they may be used to the best advantage.

Star-Star Connections

It is well known that on account of the shape of the hysteresis loop of transformer iron, the m.m.f. required to produce a sine wave of induction in a magnetic circuit of uniform cross-section made of iron will not be of simple sine wave form, but will include a third-harmonic wave; and vice versa, if the third harmonic be absent from the m.m.f. it will appear in the wave form of the induction. In the primary of a star-connected group of transformers the sum of the three currents flowing towards the neutral point must be zero; consequently, the third harmonics of the magnetizing currents in each phase, being of the same phase, are

suppressed and a third harmonic appears in the e.m.f. between the neutral and the supply mains.

The presence of the third harmonic in the e.m.f. between the neutral and mains of the primary circuit does not materially affect the e.m.f. between lines in the secondary circuit, but a load cannot be taken off between the neutral point and lines because this e.m.f. is unstable, that is to say, the neutral point will shift. The reason for this is evident and needs no explanation. If the neutral point of the secondary circuit be grounded, the secondary line terminals will have a third-harmonic pulsation to ground which may cause serious disturbances in neighboring telephone circuits.

In single-phase transformers and three-phase shell-type transformers this third-harmonic component of the wave form may be entirely eliminated by using an interconnected star secondary winding; and if care be taken properly to interlace the windings, the neutral point will be stable and a load may be taken off the secondary circuit between the neutral and lines.

If the neutral point of the primary winding be connected to the neutral point of the generator the secondary neutral point will be stable, and loads may be supplied between the neutral point and the lines; but, since the generator itself may have a third-harmonic component in the e.m.f. between neutral and terminals-it is not advisable to ground the neutral point of the secondary winding. If, however, the secondary winding be in interconnected star, the neutral point may be grounded without causing trouble.

In three-phase transformers of the form of construction known as core-type, that is to say, transformers with interlinked magnetic circuits, this same interchange of m.m.f. takes place between the phases, so that each phase has part of the required m.m.f. supplied from the other two phases during a portion of the cycle. The sum of the three magnetic fluxes must be zero and therefore the sum of the three induced e.m.fs. must also be zero, and thus the neutral point is the centroid of the primary voltage triangle. In such transformers, due to the above-mentioned interchange of third-harmonic m.m.f., there exists a third-harmonic leakage field in the air external to the coils. The neutral point will be symmetrical, even with wide differences in the permeability of the cores, the required m.m.fs. for the three cores

being supplied in the proper relation by the three primary windings. The magnetizing currents in three-phase transformers of this type which are unsymmetrical have third-harmonic components, which are in three-phase relation and produce unlike waves in the three phases.

If a load be taken off the secondary of a three-phase transformer of the type under discussion, a leakage field is set up in the coil spaces between the loaded phase and the other two, which is usually large. The regulation of such transformers for loads between the neutral and lines is not usually good. The condition is similar to the effect of loading one side of a single-phase core-type transformer connected for three-phase distribution which had not been designed with cross-connected secondary windings. Interconnection of the primary or secondary windings is one remedy for this trouble.

If a three-phase transformer or group of single-phase transformers be intended to operate with the neutral of the primary connected to the neutral of the generator, the primary winding should not be interconnected, because thereby the impedance to the flow of the third-harmonic current set up by the third-harmonic component in the generator e.m.f. wave between neutral and terminals is rendered very small and these currents may be large enough to cause undue heating.

In the straight star-connection with single-phase transformers, the voltage stress per turn on the windings is quite high on account of the excessive peaking of the e.m.f. between neutral and lines. The core loss of the transformers is usually lower than for a sine wave e.m.f., even though the effective value of the neutral to line e.m.f. is more than 57 per cent of the e.m.f. between lines. Formerly it was considered a grave disadvantage of this connection that a short-circuited unit would cause 73 per cent increase in stress on the other two. It is not probable now that such a condition could exist without tripping the breakers, since this increase in voltage with the steel now used in transformers would result in a magnetizing current having an effective value several times the full-load value of current.

The advantage of the star-star connection of single-phase transformers is in its simplicity and low cost. It is not suitable for four-wire three-phase distribution, nor should it be operated with the neutral grounded. The transformers are subjected to an undue stress between layers and between coils on account of the distorted e.m.f. between neutral and lines.

If the neutral of the primary be connected to the neutral of a generator which has no third-harmonic component the connection may be used for four-wire three-phase transmission with or without the neutral point grounded.

If, on account of the desirability of grounding the neutral point, it is found necessary to interconnect the windings, the advantage of simplicity and low cost is lost, to a great extent.

Three-phase transformers star-star-connected may be used with or without the neutral grounded, for three-phase three-wire transmission. Light loads may also be taken off between neutral and line. Interconnecting the low-tension winding does not involve much trouble, but it is simpler to connect this winding delta, which produces the same result in a simpler manner.

Star-star-connected three-phase transformers have the same advantage as single-phase transformers connected in the same manner, and the stress to which the insulation is subjected may be reduced to a smaller value for a given voltage between terminals than with any other connection; this advantage, however, is of little consequence when the line e.m.f. is low. They have the additional advantage that the e.m.fs. between neutral and lines do not have a third harmonic.

Delta-Delta Connection

This connection is the most widely used of all three-phase connections, and is recommended for moderately high voltages on account of its extreme flexibility.

The third harmonic and its multiples are eliminated in the terminal e.m.fs. of a symmetrical star-connected generator, and if the three delta-connected transformers are alike in design and magnetic characteristics they will be absent in the secondary e.m.fs. Differences in characteristics of the transformers are corrected in this connection by interchange of m.m.f. through the secondary windings. A marked dissymmetry in the bank of transformers may cause a third-harmonic component in three-phase relation to appear in the secondary e.m.f.s between lines; but the usual third-harmonic distortion characteristic of the secondary e.m.f. of single-phase transformers is not present in the e.m.f. between phases, due to the fact that the delta-delta connection affords a low impedance path to the flow of current set up by such a component, thereby automatically eliminating it. In three-phase transformers of the form known as core-type, the interlinking magnetic circuits of the three phases somewhat

modify the interactions between the three phases, but the differences in action from single-phase transformers connected in delta are trifling.

The chief advantage of the delta-connected group of single-phase transformers lies in its flexibility. If one of the transformers in a group fails, the other two are able to supply power at a diminished rating, the only change being the cutting out of the defective transformer, which may be done without interference with the operation of the other two.

The stresses to which the insulation is subjected are higher than in the star connection, and there is no means of grounding the neutral except through the intermediary of an interconnected star group of single-phase auto-transformers or a three-phase auto-transformer, or some such device, provided with a star connection.

Star-Delta and Delta-Star Connection

These methods of connecting transformers have been the subject of a good deal of controversy, and have suffered through misapplication. It was pointed out that in the star-star connection it was necessary to interconnect the primary winding to eliminate the distorting third harmonic and to obtain a stable neutral point; this is effected in the delta-star connection at a minimum cost, and with a maximum degree of stability of the neutral point. It is in reality a more direct transformation than the delta-delta connection; since there can be no interchange of m.m.f. between phases, the secondary neutral to line e.m.f. is the same as that obtained with single-phase transformation and may contain a trace of third harmonic as in single-phase transformers due to the reactive drop of the exciting current.

The three-phase core-type transformer with delta-star connection has a stable neutral point and also on account of the interlinked magnetic circuits the secondary neutral to line e.m.f. is absolutely free from third harmonic. The three-phase shell-type does not differ materially from three single-phase transformers.

The star-delta connection has some very interesting peculiarities, lack of understanding of which has led to its improper use, resulting in troubles which have been considered as the fault of the connection, rather than of the individuals who misapplied it. In this connection the sum of the secondary induced e.m.fs. must be zero on account of the delta-connected secondary, consequently the neutral point of the primary star connection

must be the centroid o' the primary e.m.f. triangle, except for the slight distortions caused by the drop due to the exciting currents in the windings. It has already been pointed out that a third-harmonic component is required in the m.m.f. wave to produce a sine wave of induction. If, therefore, the primary is star-connected, from what source is this third-harmonic m.m.f. supplied? The answer is that it is supplied to each phase as required by the other two through the secondary delta-connected winding, so that there exists a circulating third-harmonic magnetizing current in the delta of transformers connected in this manner, which is equal in magnitude and time phase to the equivalent component in the normal single-phase secondary exciting current of the transformers. The effect of differences in the magnetic characteristics of transformers so connected is to cause slight dissymetry in the secondary e.m.f. waves between lines, which is due to third-harmonic components in three-phase relation which appear in these e.m.fs.

If the neutral of a star-delta-connected bank of transformers be connected to that of the generator supplying the transformer the result will be a short-circuit so far as the third-harmonic component of the generator between neutral and terminals is concerned, the flow of third-harmonic current being limited only by the impedance of the transformers, and very serious heating may result, both to the generator and to the transformer. Since the neutral of the transformer is stable there is no necessity for connecting it to that of the generator, and if it is desired to ground the primary system this may be done most advantageously by grounding the neutral point of the bank of transformers.

The delta-star-connected three-phase transformer, or bank of transformers, is suitable for three-phase transmission and distribution with both three and four wires. A load taken off between neutral and line will cause the neutral to shift only an amount equal to the impedance drop of the transformer supplying the loaded phase. In four-wire three-phase systems, where the e.m.f. is stepped up through delta-star transformers, and three-phase power is supplied through star-delta step-down transformers, the latter, if their neutral be connected to the neutral, serve as balancers for loads taken off between neutral wires and lines. Fig. 1 will suffice to explain this action of the star-delta-connected bank of transformers. A small bank of star-delta-connected transformers in the neighborhood of a heavy unbalanced load taken off between neutral and lines at the end of a long feeder,

is, on account of this characteristic, liable to be overloaded if its neutral be connected to the neutral wire.

An interesting peculiarity of these connections is that when the wave form of applied e.m.f. is not a sine wave, a peaking harmonic in the e.m.f. across the lines will produce a flattening harmonic in the e.m.f. between neutral and lines, and vice versa, although the effective values will be in the ratio of 1 to $\sqrt{3}$, as for a sine wave; as a consequence the core loss of a three-phase star-delta-connected transformer may have different values when measured on the star side and delta side, when the form factor of the impressed wave differs from that of a sine wave.

The star-delta and delta-star connection has all the advantages of the star-star connections without their grave disadvantages; as pointed out before, when the e.m.f. is low, there is no

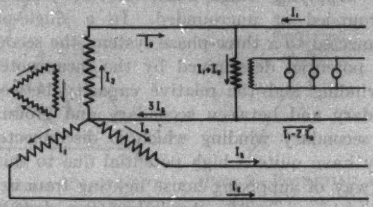

FIG. 1—ILLUSTRATING THE REGULATING EFFECT OF A STAR-DELTA-CONNECTED GROUP OF TRANSFORMERS ON A THREE-PHASE FOUR-WIRE SYSTEM.

inherent advantage in the star connection; actually there may be decided disadvantages. There is no advantage in supplying a single-phase load from the neutral point of a generator, on the contrary the single-phase output of a three-phase generator is greatest when the power is supplied from two terminals. The delta-star connection permits of this and therefore increases the unbalanced capacity of the whole system. Consequently, even should it be possible to entirely eliminate the third harmonic from the e.m.f. wave between the neutral and terminals of a generator, the star-star connection is hopelessly out of the running when it has to compete with the delta-star connection. In three-phase transformers the delta-star connection is the most economical way of obtaining good regulation between neutral wire and lines in a three-phase four-wire system.

Discussion of Delta-Delta and Delta-Star Systems

In the following part of this paper the discussion will be confined to the last two systems of three-phase connections; the proper field for each will be pointed out and the reason given for the selection.

For three-phase transmission at moderate voltages, say up to 33,000 volts, the advantage lies with the delta-delta connection for single-phase transformers, on account of its greater flexibility and because the failure of one unit in a bank interrupts service for only the short length of time required to cut out the defective unit, operation being continued with the transformers connected in V at a reduced rating.

For three-phase four-wire distribution the delta-star and star-delta-connected transformers are most suitable. It may not be out of place here to sound a note of warning in connection with supplying single-phase service from three-phase sources grounded or ungrounded. In a single-phase transformer connected to a three-phase system, the secondary winding has a potential determined by the mean potential of its primary winding and the relative capacity between primary and secondary and between secondary and ground. An ungrounded secondary winding which is disconnected from its wiring may have quite a high potential due to this effect. A preferable way of supplying house lighting from a three-phase line would be by means of a three-phase step down transformer or bank of single-phase transformers having secondaries connected in star-delta or interlinked six-phase, then if the supply circuit were grounded at the neutral point, the secondary circuit could be operated with safety ungrounded. The practise of running single-phase feeders from a three-phase supply to outlying districts for the purpose of supplying lighting service is bad in so far as when the secondaries are grounded it is liable to interfere with telephone service.

Turning our attention now to three-phase transmission at voltages above 44,000 volts, the problem of insulating begins to assume importance. Figs. 2 and 3 are potential diagrams of delta-delta step-up and step-down transformers and delta-star step-up and star-delta step-down transformers. The point O, the centroid of the potential triangle, is at zero potential; the potential of any portion of the winding of any phase is given by the distance of the equivalent point on the potential diagram from the centroid. The e.m.fs. and instantaneous

potentials are given by the projection of the points A B C, a b c on a given line passing through O, the triangle A B C, it being considered as rotating about O so as to make one complete revolution per cycle. Comparing these two potential diagrams, it will be apparent that the high-tension winding of the delta-star transformer is subject to lower average stress than that of the delta-delta, varying in the first connection from 0 to 57.7 per cent of the line e.m.f. and in the second connection from 28.8 per cent to 57.7 per cent of the line e.m.f.

The tendency of any connection to give trouble during switching will probably depend largely on the amount of potential energy stored in the system under normal operating conditions. The high-tension windings of the transformers

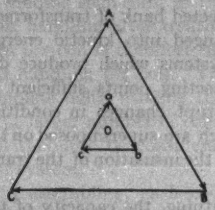

FIG. 2—POTENTIAL DIAGRAM OF DELTA-DELTA CONNECTED BANK OF TRANSFORMERS, NORMAL OPERATION.

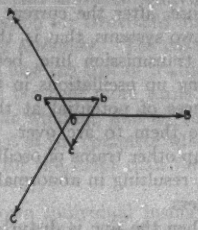

FIG. 3—POTENTIAL DIAGRAM OF DELTA-Y OR Y-DELTA CONNECTED BANK OF TRANSFORMERS, NORMAL OPERATION.

in both connections will have about the same capacity to ground, the tendency being for higher values in the transformers for the delta-delta connection. If v be the effective value of the e.m.f. between lines, the maximum amount of energy stored in the dielectric will be in the case of the delta-delta connection for each transformer $\frac{CV^2}{6}$, and in the case of the delta-star connection it will be $\frac{CV^2}{9}$ for each transformer, the value C being the total capacity of the high-tension winding of each transformer to ground.

It follows in consequence that there will probably be fewer disturbances caused in a transmission system when a star-

delta bank is switched on and off the circuit than when a delta-delta bank of the same capacity is switched on and off; and therefore the insulation stresses due to switching in the star-delta connection will be correspondingly smaller than in the delta-delta connection.

The same relations hold true for any conditions that may arise in operation which causes the breakers to open, such as a ground on the line, short circuits between phases, etc. In every case the energy stored in the dielectric is less for the star-delta-connected group than for the delta-delta-connected group.

The dangers arising from switching are caused not so much by the rapid interruption of large currents (for as a matter of fact the rate of diminution at the instant of interruption is not very much greater than if the breaker remained closed), as because, after the current has ceased, the potential energy in the two systems, that is, the disconnected bank of transformers and transmission line, becomes changed into kinetic energy, setting up oscillations in the two systems which produce differences of potential at the disconnecting points sufficient to cause them to arc over. These abrupt changes in condition set up other trains of oscillation which are superimposed on the first, resulting in abnormal stress on the insulation of the transformers.

When the line is disturbed by lightning, the capacity of the transformers will have little to do with the severity of the disturbance. The charge due to a thunder-cloud, when released, sets up waves which on striking the transformers cause a high stress between adjacent turns of the windings, particularly those near the terminals. A large capacity between adjacent turns will tend to reduce the severity of these stresses. In the star high-tension winding the large wide conductors tend to large values of capacity between adjacent turns, which is the condition required for reducing the stresses.

The delta-star grouping has the advantage from an insulation standpoint even if the neutral point is not grounded. With a grounded neutral point the insulation stress is still further reduced, an advantage which cannot be obtained with the delta-delta system without auxiliary star-delta transformers.

The mechanical stresses due to short circuit will be the same for both systems, but delta high-voltage windings are not so well adapted to withstand mechanical shock as the stauncher windings for star connection. It may therefore be stated that,

with equal mechanical support, the delta high-voltage winding will be mechanically weaker than the corresponding star winding.

Considering the two systems from the point of view of cost, let the cost of winding the coils be considered first of all. The coils used in all power transformers of large capacity are discoidal, sometimes termed pancake coils, and consist of spirally wound flat copper ribbon conductors insulated with sleeves or strips of micanite or other insulating material. To enable the workman to produce a servicable coil the conductor must be large enough to hold down the sleeves or layers of insulating materials, otherwise the coil will be "mushy". However carefully a "mushy" coil may be clamped up and treated it can never be as strong mechanically as one more solidly constructed of heavier conductor. More care is therefore involved in winding such coils, in their preparation for treatment and in their handling after treatment, during assembly. The cost per turn per coil is therefore higher, as is also the cost of treatment and handling per coil. There are 73 per cent more turns in a complete delta winding than in a star winding, and an equivalent larger number of coils. The cost of the complete winding will therefore be considerably more for the delta than for the star system.

In assembling, each coil has its own individual insulation; each lead must be tied to its proper position. The coils in a group must be placed in position one by one during assembly and the connections soldered. There are therefore more operations in the assembly of a delta winding than in that of a star winding and the coils have to be handled with more care. The cost of assembly will therefore be higher for the delta-connected than for the star-connected transformers.

Since the conductor to be insulated is smaller in the transformers of the delta group than in those of the star group, the insulation will occupy relatively more space in the former than in the latter, with the result that the dimensions of the transformers for delta connection will be larger and require more active material than those for the star connection.

A transformer designed for delta-star connection is less costly to manufacture than one designed for delta-delta connection. The high-tension wiring of a group of star-connected transformers is simpler than that for one of delta-connected units, which is no inconsiderable advantage with high transmission voltages.

Possibilities of Development

The above discussion applies to present standard practise. Considered from the point of view of future development, the advantage is all with the delta-star and star-delta connections. Thus, for example, the worst condition of stress in the transformers arises when one line becomes grounded. Figs. 4 and 5 are the potential diagrams for such a condition. The delta group has a maximum stress varying from line voltage to 87.7 per cent of the line voltage; in the star group the maximum stress varies from line voltage down to 57.7 per cent of the line voltage. If full advantage be taken of this difference, the transformer for star connection will be lowered still further in cost.

With the advantage afforded by grounding the system at

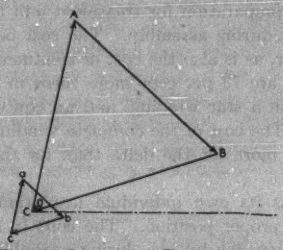

Fig. 4—Potential Diagram of Delta-Delta Connected Bank of Transformers—One Line Grounded.

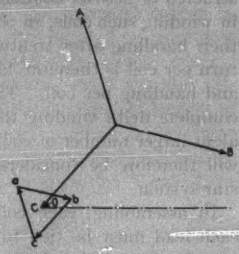

Fig. 5—Potential Diagram of Delta-Y or Y-Delta Connected Bank of Transformers—One Line Grounded.

the neutral point, the star-connected group may be manufactured at a very much lower cost than the delta-connected group.

As improvement in methods of switching will enable the manufacturer to take further advantage of the lower stress to which the star-connected group is subjected under operating conditions, considerable development may therefore be expected in this direction in the future.

Past and Present Practise

In view of the fact that the largest and most successful power transmissions in America are operated with delta-star step-up and star-delta step-down transformers, and that several among them, together with a large number of smaller power companies,

NAME	Operating voltage	Frequency (cycles)	Capacity of plant (kilowatts)	Beginning of operation	Phases	Step-up Trans. Conn. Low tension	Step-up Trans. Conn. High tension	Y-grounded direct or through resistance	Step-down Trans. Conn. Low tension	Step-down Trans. Conn. High tension	Dist. of transmission (miles)
Pacific Light & Power Co.	150,000	50	59,500	1913	1	Δ	Y	D.	Δ	Δ	241
Au Sable Elec. Co.	140,000	60	19,000	1912	1	Δ	Δ	No	Δ	Δ	245
Southern Sierras Power Co.	140,000	60	8,750		1	Δ	Y	R.	Δ	Y	239
Utah Power & Light Co.	130,000	60	42,000	1914	1	Δ	Δ	No	Δ	Δ	135
Pacific Gas & Electric Co.	125,000 to 110,000	60	25,000	1913	1	Δ	Y	D	Δ	Y	110
Tennessee Power Co.	120,000	60	15,000	1914	3	Δ	Δ	No.	Δ	Δ	140
Connecticut River Transmission Co.	120,000	60	14,400	1914	3	Δ	Y	D.	Δ	Y	60
Inawashiro Hydro-Electric Power Co.	115,000	50	42,000	1914	1	Δ	Δ	No	Δ	Δ	144
Grand Rapids Muskegon Power Co.	110,000	30	9,000	1906	1	Δ	Δ	No	Δ	Δ	35
Ontario Hydro-Electric Commission	110,000	25	106,800	1910	1	Δ	Y	R.	Δ	Y	90
Lauchhammer A. G.	110,000	50	15,000	1911	3	Y	Y	No	Y	Y	35
Georgia Ry. & Power Co.	110,000	60	50,000	1912	1	Δ	Y	R.	Δ	Δ	210
Alabama Interstate Power Co.	110,000	60	48,000	1913	1	Δ	Y	R.	Δ	Y	150
Mississippi River Power Co.	110,000	25	112,500	1913	3	Δ	Y	D.	Δ	Δ	144
Mexican Northern Power Co.	110,000	60	26,000	1914	1	Δ	Y	R.	Δ	Y	157
Lehigh Coal & Nav. Co.	110,000	25	30,000	1914	1	Δ	Y	R.	Δ	Δ	24
Ebro Irrigation & Power Co., Ltd.	110,000	50	50,000	1914	1	Δ	Δ	No	Y	Δ	105
Chile Exploration Co.	110,000	50	40,000		3	Y	Y	No	Y	Y	86
Sierra-San Francisco Power Co.	104,000	60	34,000	1910	1	Δ	Y	D.	Δ	Y	138
Yadkin River Power Co.	100,000	60	24,000	1912	3	Δ	Y	D.	Δ	Δ	96
Great Falls Water Power & Townsite Co.	102,000	60	21,000	1910	1	Δ	Δ	No	Δ	Δ	150
Central Colorado Power Co.	100,000	60	10,000	1909	1	Δ	Δ	No	Δ	Δ	152
Great Western Power Co.	100,000	60	50,000	1909	3	Δ	Δ	No	Δ	Δ	154
Southern Power Co.	100,000	60	75,000	1909	1	Δ	Y	R.	Δ	Δ	210
Shawinigan Water & Power Co.	100,000	60	45,000	1911	3	Δ	Y	R.	Δ	Δ	87
Los Angeles Aqueduct	100,000	50	22,500	1914	1	Δ	Y	D.	Δ	Y	47
Tata Hydroelectric Co.	100,000	50	40,000	1914	1	Δ	Δ	No	Δ	Δ	43
Appalachian Power Co.	88,000	60	20,610	1912	3	Δ	Δ	No	Δ	Δ	75
Rio Janeiro Tramway, Light & Power Co.	89,000	50	48,800	1913	1	Δ	Δ	No	Δ	Δ	51
Sao Paulo Elec. Co.	88,000	60	30,000	1914	1	Δ	Δ	No	Y	Δ	56
Mexican Light & Power Co.	85,000	50	58,500	1910	1	Δ	Y	D.	Δ	Y	109
Victoria Falls & Transvaal Power Co.	84,000	50	40,667	1913	3	Δ	Y	R.	Y	Δ	30
Toronto Power Co.	85,000	25	80,000	1914	1	Δ	Δ	No	Δ	Δ	80
Katsura Gawa Demryoku Kabushiki Kaisha	77,000	50	22,400	1912	1	Δ	Y	R.	Δ	Y	48
Southern California Edison Co.	75,000	50	20,000	1907	1	Δ	Y	D.	Δ	Y	117
Hidro-Electrica Espanola Molinar	70,000	50	22,500	1910	3	Y	Y	No	Y	Y	158
Pennsylvania Water & Power Co.	70,000	25	71,500	1910	3	Δ	Y	R.	Y	Δ	40

have been in operation for a considerable length of time, it seems somewhat superfluous to bring up arguments in support of this method of connecting transformers. Following is a list of power transmissions using transformers star-connected on the high-tension side which have been in operation for a considerable length of time.

Ontario Power Company	66,000 volts.
Southern Power Co	100,000 "
Ontario Hydroelectric Power Company	110,000 "

The table on p. 765 gives a list of power companies transmitting at 70,000 volts and above; 22 out of 37 of these use transformers which are star-connected on the high-tension side. One of the most recent is the large power development of the Mississippi River Power Co., the Keokuk development transmitting power at 110,000 volts. Perhaps the most notable of recent power developments is that of the Pacific Light and Power Company, transmitting at 150,000 volts, which employs the delta-star connection.

It will be evident from this table that the advantages of the delta-star connection are recognized by a large number of engineers; but it should be used universally for transmission voltages above 66,000 volts instead of in a little more than 50 per cent of the cases as the table indicates.

Conclusions

For transmission voltages below 44,000 volts, either transformers with star or delta-connected high-tension windings may be used; the delta connection has a slight advantage due to its greater flexibility. For transmission voltages above 44,000 volts, transformers with star-connected high-tension windings should be used.

This conclusion is upheld by sound reason and also because it has been tried out successfully on some of the largest transmissions in the world, several of which have been operating successfully for a number of years.

Presented at the 206th Meeting of the American Institute of Electrical Engineers, Pittsfield, Mass., May 29, 1914.

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EXPERIENCE OF THE PACIFIC GAS AND ELECTRIC CO. WITH THE GROUNDED NEUTRAL

BY J. P. JOLLYMAN, P. M. DOWNING AND F. G. BAUM

ABSTRACT OF PAPER

The paper gives an outline of the distributing system of the Pacific Gas and Electric Company of California which operates at 60 kv., the transformers being Y-connected, with the neutrals solidly grounded. The company considers the grounded neutral system has a number of important advantages with regard to the transformers, the transmission lines, and operation.

The fewer turns of larger capacity of the Y-connected transformers and the fixed lower average voltage to ground greatly increase their reliability.

The maximum voltage on the line insulators with the grounded neutral is never more than 57.7 per cent of the line voltage, and it is possible to maintain polyphase service at a substation on a branch line with only two wires in case one wire should be cut out. This cannot be done on a delta system unless one phase of the system be grounded, which is very undesirable.

With a grounded neutral, a wire down is instantly detected and power must be shut off. In a delta-connected system an arcing ground is often followed by surges which break down the insulation at other points, the cause of this disturbance being the oscillatory character of the arc. In the grounded Y system no such disturbances occur, as the frequency of an arc to ground is the same as that of the system and any damage is confined to the point of failure.

It is also believed that operation with the grounded neutral causes less disturbance in telephone and telegraph lines than would be the case in delta-connected lines.

THE PACIFIC Gas and Electric Company operates a very extensive 60-cycle transmission network in Central California. The 60-kv. system comprises about 1260 miles (2027 km.) of three-phase circuit. It is supplied directly by nine hydroelectric plants having an installed generator capacity of 67,310 kw. and three steam plants having an installed turbo-generator capacity of 68,000 kw. In addition there are 14,300 kw. of steam engine-driven generators in the company's steam plants which are held in reserve. The 100-kv. system which has just been put into operation has one hydroelectric generating station of 25,000 kw. capacity and 109.5 miles (176 km.) of circuit. The entire output is fed into the 60-kv. system through one substation.

For the purpose of the receipt or delivery of power the 60-kv. system is connected as follows: at Chico to the 60-kv. system of the Northern California Power Company; at Santa Rosa with the 60-kv. system of the Snow Mountain Water and Power Company; at a point near Folsom with the 60-kv. system of the Western States Gas and Electric Company; and at Oakland, through transformers, with the 100-kv. system of the Great Western Power Company.

These connections very considerably increase the length of circuit and total generator capacity connected to the 60-kv. system. The entire 60-kv. and the 100-kv. systems are usually operated in parallel.

The transformers at all the company's own generating stations and at all important substations have their high-tension windings Y-connected with the neutral solidly grounded. The low-tension windings of the generating station transformers are nearly all delta-connected as are also about half of the substation transformers. The remaining substation transformers have both windings Y-connected with solidly grounded neutrals. In most of the substations where the low-tension windings are delta-connected, a switch is provided between the high-tension neutral and the ground, which is normally kept open. This avoids the short-circuiting of one transformer in case of a ground on the transmission system and prevents the substation being cut off from the system by the opening of the protective devices on the high-tension side of the transformers. There are over 225,000 kw. of 60-kv. transformer capacity in the company's own generating plants and substations.

The Northern California Power Company, the Snow Mountain Water and Power Company and the Western States Gas and Electric Company operate their transformers Y-connected with the neutrals solidly grounded. The connection with the Great Western Power Company is through transformers connected delta to delta. This method of connection is not theoretically correct where power is to be fed from the delta-connected transformers into the grounded Y system, because a ground on one wire of the line connecting the delta-connected source of supply with the grounded Y system will impress 173 per cent of normal voltage across the high-tension windings of two of the transformers in the grounded Y banks. The resulting disturbance in the low-tension circuits is very severe. Our experience proves conclusively that this method of connection is not desirable.

At all generating stations, and at all important junction points and substations, the 60-kv. lines are controlled by oil switches. The lines are switched out under any condition of load or short circuit as occasion demands. The lines are also switched on at full voltage. We have operated in this manner for over 10 years and have never had any failures of transformers or of line insulation which could be attributed to this method of operation.

We consider that the grounded-neutral system as compared with the delta system affords the following important advantages:

1. *With Regard to Transformers:* Transformers are wound for only 57.7 per cent of the voltage required in the delta system. The average voltage to the neutral from all points of the windings is 50 per cent of the voltage from line to neutral; that of a delta bank is 69 per cent. The product of the turns times the average voltage to neutral in the Y-connected bank is 41.8 per cent of that in the delta-connected bank. The windings have 173 per cent the current capacity of the windings of a delta transformer.

In addition there is only one line terminal per single-phase transformer, wiring for a spare unit is much simpler and the high-tension windings may be used as auto-transformers in supplying small amounts of power to lower-voltage circuits.

The connection between the Pacific Gas and Electric Company's 100-kv. system and the 60-kv. system is made with auto-transformers connected grounded Y. We believe this to be the simplest, most reliable and most efficient connection that can be made between two such systems.

Our transformers have given so little trouble that we have not had much occasion to try to maintain service with only two transformers. We have had no difficulty, however, in carrying loads up to 2000 or 3000 kw. with two transformers.

Our experience confirms our belief that the fewer turns of greater current capacity and the fixed lower average voltage to ground of the transformers greatly increase their reliability.

2. *With Regard to Transmission Lines:* The maximum voltage on the line insulators is fixed and is never more than 57.7 per cent of the line voltage. Ten years ago the pin type insulator was the only type obtainable and the low fixed maximum voltage of the grounded neutral system has unquestionably been of great assistance in securing the best service from this type of insulator.

It is possible to maintain polyphase service at a substation on a branch line with only two wires in the event one wire should be cut out. This cannot be done on a delta system unless one

phase of the whole system be grounded, and this is very undesirable.

3. *With Regard to Operation:* With the neutral grounded, a wire down is instantly detected and power must be immediately cut off. This is exceedingly important where many of the circuits run through thickly settled districts. Inasmuch as practically all our important loads are reached by two lines or are on a loop, service is not more than momentarily interrupted by a failure at one point.

A line of any length may be charged at full voltage without shifting the static neutral. It is impossible to close all phases of a circuit at exactly the same instant. In a delta system the first phase closed will increase the capacity to ground of that phase of the system and thereby draw the static neutral toward that phase. The second phase acts in a similar manner and the static neutral does not return to the center of the delta until the three phases are closed. This sudden shifting of the static neutral is the cause of an unnecessary strain on the insulation of the system. We know of failures from this cause on delta-connected systems.

Finally, and most important of all, is the fact that in extensive high-voltage delta-connected systems a ground is often followed by a disturbance of such power that breakdowns of insulation at other points take place. Such a disturbance generally results in serious damage to apparatus and service. The cause of this type of disturbance is found in the oscillatory character of the arc which takes place from a delta-connected system to ground, together with a large amount of current which will flow in such an arc if the system is extensive. In the event of a ground on a delta-connected system, the charging current, which is a function of the voltage from wire to neutral, will be increased because the neutral is shifted from the center of the delta to one corner. This increase will be about 73 per cent. The current flowing in the arc to ground may be nearly equal to the increased charging current, and this on our 60-kv. system would amount to about 400 amperes. The circuit containing the arc, line reactance and capacity from line to ground tends to oscillate. Such an oscillating arc is very likely to set up disturbances of high power, especially when there is any such current as 400 amperes involved. We have seen evidence that such a disturbance may cause high voltage to ground on the wire on which there is an arcing ground. This fact would probably cause the operation of an arcing ground suppressor to be very unreliable.

Certain districts in which we operate occasionally have heavy fogs which are carried in from the Pacific Ocean by the prevailing westerly winds. It has been our experience in these districts that lines on pin insulators have given better service when operated grounded Y at 60 kv. than when operated delta-connected for a much lower line voltage. It seems probable that the leakage over the insulators in foggy weather was sufficient to set up oscillatory disturbances which caused more trouble than has the higher but more stable line voltage.

We have found that the grounded Y system is entirely free from such disturbances as these. The frequency of an arc to ground is that of the system. Any damage is confined entirely to the point of failure. The short-circuit currents have not caused any damage to generator or transformer windings. Due to the distribution of the sources of power, any given point on the system will have a good many miles of line between it and several of the generating plants. Hence it is doubtful in many cases if more current would flow in a short circuit to ground than would flow to ground if the system were delta-connected. The drop over the lines from the more remote generating plants to a point at which a ground may take place, serves to prevent the voltage at points removed from the trouble from dropping to zero, and therefore the service is not seriously interfered with except in the vicinity of the trouble.

We believe that the operation of our system with the neutral grounded causes less disturbance in the circuits of our neighbors, the telephone and telegraph companies, than would be the case if we operated delta-connected.

Briefly, the induction in parallel telephone or telegraph circuits is caused principally by any unbalanced currents in the phases of the high-tension circuits, that is, currents returning through the ground, and by the presence of voltage to ground on the line conductors. The last cause is by far the most important, because the unbalanced currents during normal operation may be kept very small, while the voltage to ground is always high. A ground on the grounded-Y system will not cause much, if any, more current unbalanced than will a ground on a delta-connected system. The unbalanced current is at normal frequency on the grounded-Y system instead of at a very much higher frequency as is usual on the delta-connected system, hence the parallel circuits are not affected so unfavorably. It is our experience that even a considerable amount of unbalanced current at the normal 60-cycle frequency has little noticeable effect on

parallel telephone circuits. The unbalance will be immediately removed from the grounded-Y system in all cases, whereas a delta-connected system may occasionally be operated a short time with a ground before a final shut-down takes place. The definite limit on the voltage to ground is of very great advantage to the parallel circuit.

Conclusion

The operation of our high-tension network with the grounded neutral has been entirely satisfactory. We do not believe that we could give as good service, with as high a degree of safety to the public, with any other system.

DISCUSSION ON "INFLUENCE OF TRANSFORMER CONNECTIONS ON OPERATION" (BLUME), "A STUDY OF SOME THREE-PHASE SYSTEMS" (FORTESCUE), AND "EXPERIENCE OF THE PACIFIC GAS & ELECTRIC CO. WITH THE GROUNDED NEUTRAL" (JOLLYMAN, DOWNING AND BAUM), PITTSFIELD, MASS., MAY 29, 1914.

Guido Semenza (by letter): Italy is one of the countries of Europe which has largely developed the electric transmission of power from hydroelectric installations. In fact there are in Italy, the area of which is about double that of the State of New York, more than 2400 hydroelectric power houses, nearly all of them provided with transmission and distribution lines.

It may be of some interest to you to know the general opinion in this country on the problem under discussion.

The writer recently questioned the engineers of several Italian plants in order to have their opinion: The power of these plants varies from a few thousand kilowatts to 40,000 kw., with transmission by overhead lines at voltages varying from 6000 to 88,000 volts and by underground lines up to 25,000 volts.

First, concerning overhead high-tension transmission:

a. The great majority of the systems are delta-connected, consequently insulated from the ground.

b. A few are Y-connected with a spark gap (horn-arrester) between the neutral points and the ground.

c. A few have a real grounded neutral point across a resistance of some kind.

d. Only two to my knowledge have the neutral point grounded without resistance, (which I will call a short ground).

Second. Concerning underground high-tension lines: No system of this kind is known with grounded neutral, either with or without resistances.

Third. Concerning low-tension distributions: All sorts of arrangements are to be found, insulated delta, grounded Y, four-wire three-phase with grounded neutral, etc.

It must be noted that the first three-phase transmission plants constructed in Italy were planned with delta insulated connection, and their operation having proved satisfactory from the beginning, the same arrangement has been generally adopted all over the country.

Only later, in some installations in which a number of disturbances were noticed, as a trial, the neutral was grounded both in the power house and at some extreme point of the distribution; in some cases the practise proved to be good, as some of the disturbances were eliminated, while in other instances the remedy had a contrary effect.

For instance, on the Subiaco-Roma line, where current is generated directly by alternators at 33,000 volts, the maker of the alternators imposed a grounded neutral; but the moment an insulator was punctured the gradient of tension was so steep that it was

dangerous to walk about in the power house, the current passing through the ground not being always sufficient to trip the circuit-breaker.

In a general way, very serious disturbances were caused in telephone and telegraph circuits.

Among the large systems, only that of the Societa Conti per Imprese Elettriche has a short-grounded neutral of 50,000- and 25,000-volt overhead lines. This is one of the systems which is improved with the grounding; but a long period of disturbances on telephone lines was experienced. At last it was found that the principal cause of these was the third harmonic, due to over-saturated transformer.

The plant of the Municipality of Milan at 60,000 volts has the neutral point grounded through a water jet discharger.

The operation is good, but on both these systems interruptions of service are more frequent when compared with other analogous plants delta-connected.

Nearly all the other large systems are delta-connected, thus insulated from the ground. I recall the Milan Edison Company (15,000 volts), the Societa del Cellina (30,000 volts), the Societa Adamello (72,000 volts), the Societa Meridonale di Elettricita (88,000 volts), the Societa Dinamo (50,000 volts), the Societa Imprese Elettriche Roma (60,000 volts), and many others.

Being personally in favor of the insulated delta arrangement, I will summarize here the reasons which are generally given in favor of this solution in my country:

1. With good circuit-breakers, a ground on line will always result in an interruption of the line. Although keeping a a line in service, with a ground on it, is not very frequent, it has sometimes occurred without giving any trouble.

2. The grounding through a resistance is an immediate solution which presents the disadvantages of both insulated and grounded systems. In fact, the disadvantage of the insulated system is said to be that full delta tension is put on an insulator when a line is grounded; but the resistance, grounded neutral, when the accidental ground has a low resistance, so that the current is high, can give such a drop on a neutral connection that the tension on the insulators may rise quite near to the full delta value.

3. Ground connection is never a sure device. Moreover, a ground is effective only locally, but not at any distance. Therefore, only one ground in a large system is not considered sufficient.

4. Short-grounded neutrals are apt to disturb all low-current circuits. (Telegraph, telephone, signaling).

5. The practise in Italy is to over-insulate lines. It is considered that money spent in using larger insulators is well spent. So the advantage of grounded neutral in cheapening the cost of lines is not of great value here.

6. One of the most serious disturbances on long-distance transmissions is the traveling surges caused by atmospheric

influence. It is not yet demonstrated that the grounded neutral has any beneficial influence on the accidents caused by such disturbances.

7. It is said that a neutral grounded prevents the accumulation of static charges. In many Italian systems this accumulation is prevented by water jet dischargers, acting on the busbars or on the line wires.

Concluding, I do not see many reasons for supporting the grounding of a neutral point, while I see many advantages in not doing it. I am persuaded that by using good insulation and good terminal protection, the insulated system affords all conditions for good and regular operation.

F. F. Brand: With reference to one of the points Mr. Semenza mentions, that is, that with the grounded Y connections, serious disturbance was found to occur in telephone and telegraph lines, I would state that this disturbance can be considered to be due to two causes—one is current and one is voltage interference. Current interference can only occur where the current flowing in the lines is in the same direction in all the lines at the same instant, that is to say, there must be a current returning through the earth. In order to get a return current through the earth, it is necessary that there should be unbalanced currents in the line, or a triple-harmonic current flowing through the earth.

In Europe it is common practise to use Y-Y-connected transformers. If the transformers are shell-type construction, there will be a triple-harmonic current flowing in the lines and a triple-harmonic return current flowing through the neutral, at the same instant, but if these machines are three-phase core-type there will be no appreciable flow of current to the neutral, due to the fact that there is practically no triple-harmonic voltage between line and neutral in the core type transformer.

With reference to the interference with telephone lines, and other voltage disturbance, there can be no great difference in the Y and delta connections.

W. W. Lewis: There are in North America, according to a statement issued recently by the *Electrical World*, (issue of April 25, 1914), 35 transmission systems operating at 70,000 volts and over, and in the remainder of the world 19 such systems. The following tabulation shows the division of these systems into Y and delta:

	Y	Delta	Not given	Total	Grounded neutral
North America	19	14	2	35	18
Remainder of the world	10	6	3	19	6
	29	20	5	54	24

From the above it will be seen that of the forty-nine systems on which data are given, 29, or about 60 per cent, are Y connected, and 24, or about 50 per cent, have grounded neutral.

In North America, however, practically all the Y-connected systems are grounded, and about 55 per cent of the total number of systems.

These figures show a remarkably close division of opinion among operating engineers as to the relative merits of grounded Y and isolated delta, with the preponderance slightly in favor of the grounded Y in North America, at least. The following tabulation shows the number of systems started up each year, beginning with 1901, when the first one was put into operation:

Year	Number
1901	1
1906	2
1907	1
1908	0
1909	3
1910	8
1911	5
1912	6
1913	7
1914	13
1915	5
	51
Not given	3
	54

It will be noted that only four of these systems were installed prior to 1909. Counting the years 1914 and 1915, when some of the systems will be put into operation, practically the total development of high-tension transmission has taken place in about seven years. It is small wonder, then, that opinion should be divided as to the best method of connection, and that practical operating men are solving the problem by the method of experiment, which is after all the only conclusive method.

In the present discussion the writer has selected a half-dozen typical systems, three of which are connected isolated-delta and three grounded Y, and will briefly discuss certain points in their operating experience.

First. Great Western Power Company. (*Isolated Delta*).

This system is the only one of importance operating isolated delta in the State of California. It runs from Big Bend to Oakland, and is about 154 miles long. At no point is the altitude over 500 feet.

The operating voltage is 100,000 volts. Operation was begun in 1909. There are two circuits on the same towers, the conductors being arranged vertically. There is one overhead ground wire at the middle of the towers.

Lightning is very infrequent (about twice a year) and no

trouble is caused by it. Short-circuits and arcing grounds cause some trouble (about once in two or three months). Arcing grounds destroy the telephone communication, break down insulators, and frequently burn off the line wire. Short circuits also necessitate shutting down the system.

At Oakland, the Great Western system is connected by delta-delta transformers to the grounded-Y system of the Pacific Gas & Electric Company. Some of the disturbances originating on the latter system, no doubt, are felt on the former system.

Second. Colorado Power Company. (Isolated Delta).

This system consists of two parts, the Shoshone-Denver line, one hundred and fifty-three miles long, and the Boulder-Denver line, twenty-eight miles long. The two lines are capable of being tied together at the Denver substation. The operating voltage is 100,000 volts. The system has been in operation since 1909. The transformers at all points are delta-connected on the high side, except at Boulder, where they are isolated-Y. The conductors are placed horizontally. There is one ground wire at the middle of the towers.

The Shoshone-Denver line runs over some of the roughest country in the United States, and at one place reaches an altitude of 13,500 feet. Lightning is severe at certain times of the year, and wind velocities of 150 miles per hour are at times recorded.

An analysis of the disturbances of this system in 1912 shows 42 per cent due to wind, 30 per cent due to lightning, and the balance due to construction failures, extraordinary causes and unknown causes.

The greatest part of the trouble is due to short circuits, caused by wires swinging together during wind storms, and by arcing grounds, due to the lines swinging against the towers or ground wire. A shut-down usually results from either a short circuit or an arcing ground.

It has been found impossible to operate the long Shoshone-Denver line with one conductor dead grounded, due to the increase in corona loss and charging current.

The short Boulder-Denver line, however, has been operated for hours with a dead ground on one line.

However, a ground on the line, either arcing or dead, interferes with telephone communication, and this usually necessitates a shut-down.

Third. Au Sable Electric Company. (Isolated Delta).

The main line of this system operates at 140,000 volts, and extends from Au Sable to Owosso, in eastern Michigan, a distance of about 160 miles. The system consists of a single circuit, the conductors being arranged two on one side and one on the other side of the tower. There is no ground wire. Operation was begun in 1912.

The lightning is very severe. The country is open and the lines are much exposed. Practically all the storms which cause interruption of service occur during the season from May to

September. Lightning causes simultaneous arc-overs from two or three lines to ground over insulators or bushings, thus resulting in phase short circuits.

Fourth. Sierra & San Francisco Power Co. (*Grounded Y*):

This system is located in California, in much the same kind of territory as the Great Western Power Company system. The line extends from Stanislaus to San Francisco, a distance of about 135 miles. The operating voltage is 104,000, the maximum altitude about 1000 feet. Operation was begun in 1910. The system consists of two circuits on the same towers, conductors arranged vertically, no ground wire. The two lines are connected in parallel on the low-voltage side. The neutrals on both ends of the line are dead grounded.

Short circuits by leaky insulators, large birds, etc., occur on an average of about once a month.

Short circuits are usually taken care of by separating the lines on the low-voltage side and cutting out the affected line. Grounds rarely develop into short circuits between phases, but the line wire or the insulators usually burn off. There is practically no lightning trouble on this system.

Fifth. Yadkin River Power Co. (*Grounded Y*).

This system is situated in North Carolina, and the main line runs from Blewett's Falls to Method, a distance of about 90 miles. The operating voltage is about 100,000 volts.

There are two circuits on steel towers, the conductors in a vertical plane, one ground wire at the middle of the towers. The neutral is dead grounded at the generating end only.

Lightning is extremely severe for several months in the year. Operation of the system was commenced in 1912, with isolated neutral; but this was changed after about a year to grounded neutral.

Grounds and short circuits are frequent. A device has been used to reduce trouble from short circuits. This consists of a relay in the neutral, which, when operated by ground current, throws a large resistance in series with the field of the generator exciter, thus momentarily reducing the voltage and allowing the short circuit to die out.

Sixth. Pennsylvania Water & Power Co. (*Grounded Y*).

This system is grounded through a resistance. The power is generated on the Susquehanna River, in southern Pennsylvania, and transmitted at 70,000 volts to Baltimore, a distance of about 40 miles. There are two sets of towers, with two circuits per tower; conductors arranged vertically; one ground wire per tower. Operation was begun in 1910.

The lightning is severe in this district and short-circuits due to insulators flashing over are frequent. Interruptions have been greatly reduced by a device which short-circuits the line at the station through a fuse, thus allowing the arc over the insulator to become extinguished. This device is supplemented by another consisting of series line relays, which act on the

generator field, opening it momentarily and then closing it, the whole action taking place so rapidly that synchronous apparatus does not get out of step. With the assistance of these auxiliary devices, operation is said to be very satisfactory.

Conclusions. It will be seen from the above that neither the isolated-delta nor grounded Y systems are free from trouble.

The amount of trouble is governed largely by location, climate and mechanical details of line construction.

Two arguments which are frequently used in favor of the isolated-delta system are proved in practise to be fallacious:

First, that only voltage troubles need be expected. On the Colorado and Au Sable systems phase short-circuits are numerous.

Second. That a delta system can operate continuously in case of a dead ground on one line. This is only true for very short lines, as on long lines the charging current—due to the increased capacity and voltage—becomes excessive, likewise the corona loss. The telephone system is also invariably disturbed, so on this account operation usually must be discontinued.

On the other hand, the short-circuit troubles on the grounded Y system are very severe, and some auxiliary short-circuiting and field-destroying devices are almost essential to render satisfactory operation.

As far as operation is concerned, it seems that both systems have their advantages and defects, and that in selecting a system, the location and climatic conditions should be carefully considered.

V. M. Montsinger: About a year and a half ago, Dr. Steinmetz and Mr. Faccioli suggested to Mr. Blume and myself an investigation of the effect of electrostatic capacity and reactance on third harmonics in Y auto-transformers.

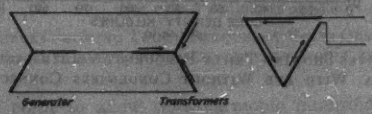

FIG. 1—DIAGRAMMATIC SKETCH OF GENERATOR AND TRANSFORMERS FOR MAKING THIRD-HARMONIC VOLTAGE TESTS. ARROWS SHOW DIRECTION OF TRIPLE-FREQUENCY VOLTS.

Some tests were made on small transformers connected as shown in Fig. 1 to determine to what extent the triple voltage was increased by electrostatic capacity supplied from condensers connected across the legs of the secondary windings. The transformers were excited from a Y-connected generator of several times the sum of the capacities of the transformers.

A rather peculiar phenomenon was found to take place, that

is, when the condensers were connected, the triple voltage, at a certain value of the core density, suddenly rose, almost in a straight line, to a value slightly over 200 per cent of the fundamental; but on increasing the core density, the triple voltage decreased almost as suddenly to approximately its normal value, corresponding to that particular density without capacity. This same phenomenon occurred also when the condensers were placed across the opening in the delta.

By connecting the transformers as shown in Fig. 1, we were able to differentiate the triple voltage from the fundamental and other higher harmonics, not multiples of the third, and to

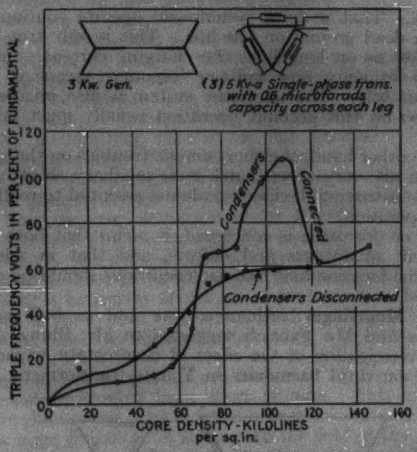

FIG. 2—CURVES SHOWING TRIPLE-FREQUENCY VOLTS OBSERVED ACROSS OPEN DELTA, WITH AND WITHOUT CONDENSERS CONNECTED ACROSS DELTA LEGS

determine the third harmonics in per cent of the fundamental voltage.

Fig. 2 shows the results of tests recently conducted with three 5-kv-a. core-type transformers connected with and without condensers, and excited by a 3 kw. generator as shown by the sketch in the upper part of the diagram.

Fig. 3 shows the same transformers and generator connections. The condensers in this case, however, were connected in an opening in one corner of the delta, and the voltage read across the condensers. In this case, as will be seen later, the condensers draw only a triple-frequency current.

For the case as given in Fig. 2, the condensers draw a complex current which is composed of the fundamental and of the triple frequency. The same condition would be true if the condensers were connected between the neutral point to the lines of the Y on the excited side of the transformer, which case represents the conditions existing with a transmission line of an isolated system connected to Y auto-transformers with the neutral point grounded.

The indications are that if we have the right conditions existing, that is, if the electrostatic capacity of a transmission line is of the proper value, and if the flux density of the transformers

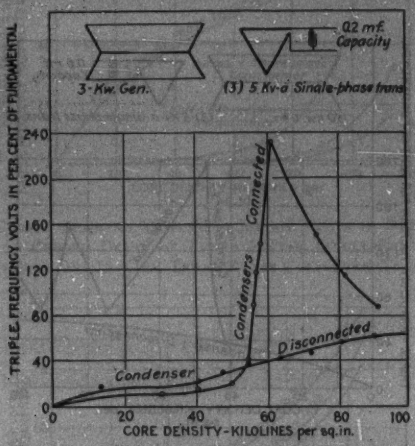

FIG. 3—CURVES SHOWING TRIPLE-FREQUENCY VOLTS OBSERVED ACROSS OPEN DELTA, WITH AND WITHOUT CONDENSERS CONNECTED

is at the point to allow third-harmonic intensification, there may be severe line disturbances which would cause strains on the line and transformer insulation.

With these transformers, excited by the small generator, as shown in Figs. 2 and 3, an increase or a decrease in the electrostatic capacity gave a smaller intensification, or peak value, of the triple-frequency volts, while with the larger generator, with practically the same transformers, the indications were that with a larger condenser capacity, the peak values would have been still larger, but on account of the condensers being of low voltage, and arcing over, higher values could not be recorded. However, since the iron in transformers is generally worked

not far below the saturation point, the third-harmonic potential peaks can never exceed, to any great extent, three times normal potential.

Fig. 4 shows the results of tests made under the same conditions as those given in Fig. 3, except that a 150-kv-a. instead of a 3-kv-a. generator was used, and that 0.6 mf. instead of 0.2 mf. capacity was connected across the opening in the delta. It will be noted that with the larger condenser capacity, the maximum triple-frequency intensification occurs at a lower core density and that after the first rise and fall, a second and third rise occur. At these peaks, after the first, a marked humming sound in the transformers indicated that the frequency was

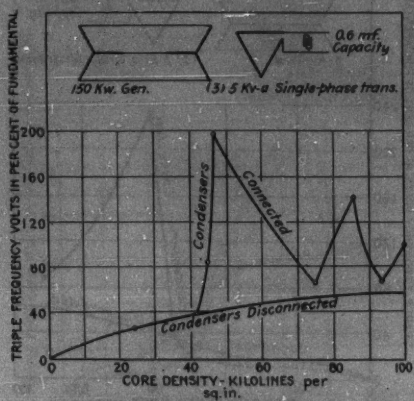

FIG. 4—CURVES SHOWING TRIPLE-FREQUENCY VOLTS OBSERVED ACROSS OPEN DELTA, WITH AND WITHOUT CONDENSERS CONNECTED

higher than a triple harmonic—probably multiples thereof. The lower curve shows the approximate minimum triple voltage existing in any group of three single-phase core type transformers or auto-transformers connected so that a third-harmonic circulating current cannot flow.

This curve, together with the current circulating in the delta when closed, is given in Fig. 5 for different core densities. Also similar voltage and current curves are given for a three-phase, 15-kv-a. core type transformer.

The curves in Fig. 6 show the effect of electrostatic capacity on the triple-frequency volts of a three-phase core-type transformer. Although a fairly large condenser capacity was placed

across the delta legs and across the opening in the delta, practically no increase was obtained in the third-harmonic volts.

Incidentally, I might mention here that this method of connecting three single-phase transformers was first proposed, I

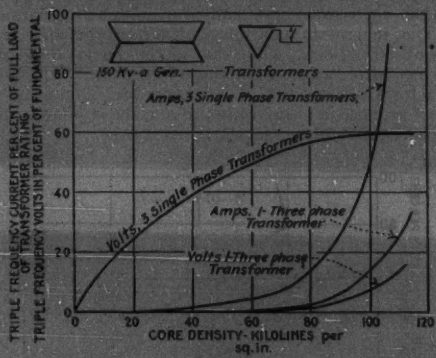

FIG. 5—CURVES SHOWING TRIPLE-FREQUENCY VOLTS IN OPENED, AND AMPERES IN CLOSED DELTA OF THREE 5-KV-A. SINGLE-PHASE TRANSFORMERS AND OF ONE 15-KV-A. THREE-PHASE CORE-TYPE TRANSFORMER

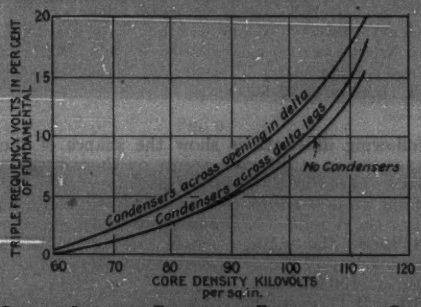

FIG. 6—CURVES SHOWING EFFECT OF ELECTROSTATIC CAPACITY ON TRIPLE VOLTAGE OF THREE-PHASE 15-KV-A. CORE-TYPE TRANSFORMERS CONNECTED Y-DELTA, EXCITED BY 150-KV-A. GENERATOR. 1.0 MF. CAPACITY ACROSS OPENING IN DELTA AND ACROSS EACH DELTA LEG

believe, by Mr. Spinelli, an Italian engineer, for transforming from three-phase to single-phase triple-frequency power under balanced conditions, by placing a load across the opening in the delta.

The results of tests made with three single-phase transformers operating at a flux density of 97 kilolines per sq. in., are shown in Fig. 7. The conditions were perfectly balanced, but the disadvantages found were: first, that the transformer efficiency was comparatively low; second, that the power factor was very poor, and third, that there was practically no voltage regulation whatever. The maximum efficiency of output divided by input was about 80 per cent, while that of the output divided by the transformer rating was only about 17 per cent. The maximum power factor was about 0.27. However, Mr. Taylor, an English engineer,* proposes a means of improving the regulation although the efficiency and power factor are still low.

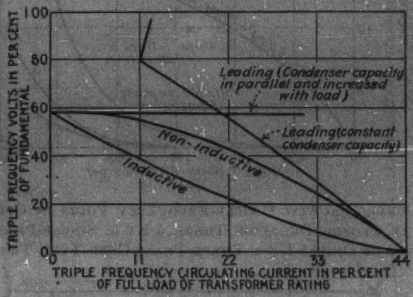

FIG. 7—CURVES SHOWING VOLTAGE REGULATION FOR LEADING, LAGGING AND NON-INDUCTIVE LOADS ACROSS OPEN DELTA OF THREE 5-KV-A. SINGLE-PHASE Y-DELTA-CONNECTED TRANSFORMERS, OPERATING AT A CORE DENSITY OF 97 KILOLINES

The following illustrations show the shapes of the current and voltage waves at different points on these curves.

Fig. 8 was taken at a density of 65 kilolines, and shows the waves of the voltage across the opening in the delta and across the lines of the Y side. No condensers were connected.

Fig. 9 shows the voltage across the leg of the delta and across the opening in the delta with condensers across the delta legs. Density 100 kilolines.

Figs. 10 and 11 show the voltage across the leg of the delta and amperes in the exciting lines. Densities 110 and 140 kilolines.

Fig. 12 shows voltage across the leg of the delta and amperes in exciting lines. Density 62 kilolines.

Fig. 13 shows voltage across the opening in the delta and across delta leg. Density 62 kilolines.

(In order to show these points of intensified triple frequency, there were set up in the hall the three 5-kv-a. trans-

*See London *Electrician*, May 8, 1914.

[MONTSINGER]

FIG. 8

[MONTSINGER]

FIG. 9

[MONTSINGER]

FIG. 10

FIG. 11 [MONTSINGER]

FIG. 12 [MONTSINGER]

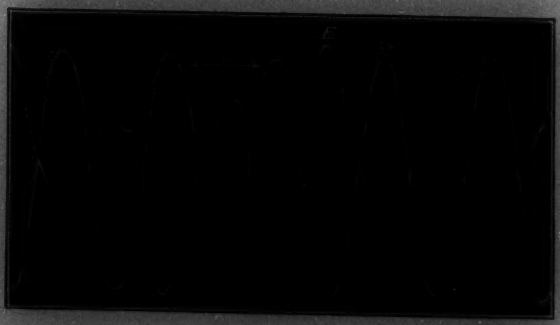

FIG. 13 [MONTSINGER]

formers and the 3-kw. generator and motor used in obtaining these curves. It was arranged that the shadow of the needle of the voltmeter, reading the volts across the opening in the delta, was thrown on the screen as it moved. The variations of the triple-frequency volts, as the flux density was increased and decreased, were shown: first, without the condensers; second, with the condensers across the delta legs, and third, with the condensers across the opening in the delta).

C. M. Davis: Does the maximum point shift up or down as the different capacities are placed across the opening in the delta?

V. M. Montsinger: This is the maximum point that I could obtain with this apparatus. If I added more condensers, the point would be lower and if I added less condensers, it would be still lower.

C. M. Davis: Does resonance, or something like that, affect it?

V. M. Montsinger: I do not think that it is a case of resonance.

C. M. Davis: If it were resonance, you would get that high peak occurring at different flux densities, would you not?

V. M. Montsinger: In some cases it does begin to rise again if we go to a still higher density, but in this case, it does not rise again; but with the larger generator, it does.

C. M. Davis: My point is that if it is a case of resonance, inserting a different capacity across the opening of the delta would cause the maximum peak to occur at different flux densities. For instance, instead of the maximum peak occurring at about 60 kilolines, with another condenser, it might occur at 40 kilolines and with still another condenser, it might occur at 70 kilolines.

V. M. Montsinger: As pointed out before, and as was shown in Figs. 3 and 4, it occurs at different flux densities for different capacities across the opening in the delta; the greater the capacity, the lower the density at which the maximum peak takes place.

L. F. Blume: The particular density at which the peak will occur depends on the electrostatic capacity, and the condition of saturation of the iron. If more capacity had been inserted, the peak would have occurred at a lower density. The reason the amount of intensification increases as the density increases, is the fact that the iron is operated at a higher degree of saturation, making the third-harmonic charging current less effective in increasing the third-harmonic voltage. I think that the phenomenon is not one of resonance, because a critical value of electrostatic capacity and reactance is not required to obtain the result. It is more analogous to the rise in voltage which takes place in a generator when delivering a leading wattless load. The third harmonic can be considered as being generated in the windings of the transformer on account of the variable permeability of the iron, which, when connected to a leading wattless load, is increased thereby.

H. S. Osborne: Several references have been made to the inductive interference caused in telephone circuits by the operation of parallel high-tension power circuits. In the paper by Messrs. Jollyman, Downing and Baum, the view is expressed that their grounded star-connected system causes less disturbance in telephone circuits than it would if connected in any other way. It should be noted that this remark is evidently given as a statement of personal opinion and not as a conclusion which has been established.

Much trouble has been caused in telephone circuits by power circuits, both of the grounded star and of the delta-connected type. There are all over the country, particularly in the State of California, many telephone toll circuits, the serviceability of which is in large measure destroyed because of inductive interference from high-tension lines with grounded neutrals, under normal operating conditions. At times of abnormal conditions on power circuits, parallel telephone toll lines or telegraph lines are put out of service by the operation or the destruction of the protective apparatus, and sometimes by the destruction also of cables or of central office apparatus. It is doubtful whether a sufficient number of comparative observations have been made of the disturbance from delta-connected and from grounded star-connected power systems under conditions which are otherwise the same, to make possible a final conclusion regarding the relative severity of the electric disturbances from these two types of power circuit when both are so constructed and operated as to minimize the interference. Taking into consideration, however, the character of the disturbances, the experience of the telephone companies throughout the country would not incline them to support the authors' view, but rather the contrary conclusion.

An attempt has been made to compare the inherent features of delta and grounded-star connections in so far as their inductive effects are concerned. In comparing the relative inductive effects from different systems, it should be remembered that if the systems were perfectly balanced, that is, if the vector sum of the voltages between the line wires and ground were zero, and current in the ground were zero, the inductive effects from different three-phase systems would be similar. In considering the different systems, the comparison should, therefore, be made of the unbalanced components of voltage and current. A delta-star-connected system with the neutral point non-grounded would have an electrical balance similar to that of a delta-delta-connected non-grounded system. The comparison has, therefore, been made between the relative inductive effects due to the unbalances which occur in the delta-delta system and the delta-star system with grounded neutral.

This comparison is summarized in a table which is given below as a part of the record of this discussion. In brief, the comparison indicates that under abnormal conditions, either

the delta-delta or the delta-star grounded system will make entirely inoperative telephone circuits which are severely exposed to them. The relative magnitude of the inductive effects under these circumstances depends largely on conditions. Under conditions of normal operation with balanced loads, the unbalances in the delta system may be reduced to a minimum. The unbalances in the grounded system may be restricted to the third harmonic and its multiples, and these may be of relatively small magnitude. With unbalanced loads, the inductive balance of the delta system remains good, but the inductive effects from the grounded system become severe.

In view of this analysis and of the experience of the telephone companies, the presumption seems to be against the grounded system. It is believed, however, that no one is at present in a position to make an authoritative statement regarding the relative inductive effects inherent in grounded and non-grounded systems. As far as I am aware no thorough study has been made of the relative possibilities of reducing interference from these two types of systems. Unless adequate measures are taken to minimize the inductive effects, the disturbances from systems of either type may be very damaging, as the telephone companies can abundantly testify.

With the rapid increase in the networks both of telephone and high-tension power circuits, it is becoming increasingly difficult to keep the two classes of circuits adequately separated. It is, therefore, becoming more and more important that power circuits be constructed and operated in such a way as to minimize the disturbances which they cause in parallel telephone and telegraph circuits. If it should be found on thorough investigation that the inductive effects from grounded and non-grounded systems are substantially different in amount when each is provided with all the precautionary measures which are practicable and reasonable, then this consideration should be given its full weight in determining which type of transformer connection should be employed.

Comparison of Delta-Delta and Delta-Star Grounded Connections for Three-phase Power Transmission Circuits from the Point of View of Inductive Interference in Parallel Telephone and Telegraph Circuits.

Delta-Delta

(a) Normal Condition of Power Circuit.

Balanced Loads:

If line is well insulated, the voltages to ground are determined by the capacities between the ground and the line wires throughout their entire length and the capacities of all other

Delta-Star Grounded

(a) Normal Condition of Power Circuit.

Balanced Loads:

Voltages to ground balanced to somewhat higher degree than transformer windings.

No fundamentalcurrent through neutral. Third harmonic magnetizing current and its multiples

lines in direct metallic connection to the line under consideration. Voltages to ground will be balanced provided entire system is so transposed as to equalize capacities between line wires and ground, and provided system is without leaks.

Under these conditions no current will flow in the ground except a very small charging current between adjacent transposed sections.

Unbalanced Loads:

Voltage unbalance to ground is caused by differences in impedance drop in the different phases. This effect small.

Currents in ground limited to unbalanced charging current. This effect small.

(b) Abnormal Condition of Operation.

One Wire Open:

Makes power system inoperative. Causes severely unbalanced voltages and severe interference in telephone circuits.

One Wire Grounded.

Not always discovered by power company. Voltages unbalanced throughout entire system with correspondingly severe disturbances in telephone systems. There is a danger of high-frequency oscillations due to an arcing ground, although there is no record of trouble experienced by the telephone companies which has been definitely traced to this specific cause. In a great many cases the voltage unbalance with one wire grounded without the occurrence of an arc is of itself sufficient to render parallel telephone circuits inoperative.

circulate in delta windings. A sufficient amount flows through neutral connection and ground to provide e.m.f. for circulating currents. Currents flowing in ground may therefore be small but may cause disturbance in telephone circuits because of exquisite sensitiveness of telephone apparatus to currents of frequencies of the third and higher harmonics of 60-cycle systems. These harmonics are not essential to the operation of the power system, and means can possibly be found to prevent their flow through ground.

Unbalanced Loads.

Voltage unbalance to ground is caused by differences in impedance drop in the different phases. This effect is small.

Current unbalance equivalent to difference in load currents flows through neutral and ground. A small current causes relatively very severe inductive effects because locus of current in ground is far below surface and because current contains harmonics in addition to fundamental.

(b) Abnormal Condition of Operation.

One Wire Open:

Not always immediately discovered by power company. The total load current carried by the two conductors which remain in service returns through ground. Disturbances in telephone circuits very severe.

One Wire Grounded:

Makes power system inoperative. Heavy current flowing through fault supplied from many lines in an inter-connected system gives very severe and widespread disturbances in parallel telephone circuits

F. E. Haskell: Is the inductive disturbance chiefly electrostatic or electromagnetic; that is, to what extent will each kind occur?

H. S. Osborne: The question is asked whether inductive disturbance is chiefly electrostatic or electromagnetic. The relative importance of these two effects depends very largely indeed on the conditions of individual cases. Note should be made, however, of a marked difference in the ease with which the zone of serious electrostatic and electromagnetic effects can be limited.

The presence near the power wires of conducting or partially conducting bodies, such as overhead grounded wires or the earth, is much more effective in restricting the electrostatic field than in limiting the electromagnetic field. This difference arises partly from the fact that relatively small charging currents are sufficient to largely influence the electrostatic field and relatively large circulating currents are necessary to considerably limit the electromagnetic field. Unbalanced current from the power circuit flowing in the ground does not behave as though the ground were a perfect conductor, but distributes itself very widely and causes correspondingly widespread inductive effects. Generally, telephone and telegraph circuits have not been subjected to severe electrostatic disturbances, provided they are more than 200 or 300 ft. away from the disturbing circuit. Severe electromagnetic disturbances have, however, been experienced at considerably greater distances from the power circuits. An extreme case of electromagnetic induction is represented by the New Haven Railroad, which caused serious electromagnetic induction in telephone circuits about five miles from the disturbing circuits.

C. O. Mailloux: There is one point the speaker might have emphasized. The effects from electrostatic action are due to the combined effects of the line, whereas the electromagnetic effects are due to current passing through the line. That was clearly shown in the case of the very high potential transmission system in Michigan, a system employing over 140,000 volts, where the electrostatic induction in a telephone line situated at considerable distance from the power line was quite marked. That is clear from the fact that we know that electrostatic induction depends upon the potential of the line, whereas electromagnetic induction depends upon the magnetic field, which is itself a function of the current flowing through the line. The matter is of great interest, and I hope there will be discussion on it.

E. E. F. Creighton: In regard to the relative value of electrostatic and electromagnetic induction effects, it seems to me the electromagnetic effect from power circuits is and always will be a greater menace to telephone lines and any other parallel lines. The electrostatic can be taken care of in many ways that are practicable, but the electromagnetic seems to use such a depth of the earth, and forms such a large loop in conjunction

with the telephone line, that it makes it impossible to screen it in any way.

Some tests were made some time ago where the distance between the lines was 30 feet—they were on opposite sides of the roadway. The power line was grounded at the further end and the current was returned through the earth where there were salt marshes and consequently where one would expect the current to flow through the highly conducting surface. The values of induction between these two circuits were measured and from these measurements calculations were made of the equivalent loop of the primary and secondary, considering them simply as a transformer with one turn on the primary and one on the secondary. The equivalent loop gave a depth to the center of the current in the earth of 260 feet below the surface, consequently, although the wires were only 30 feet above the surface, one must consider the equivalent return circuit as at a great depth, and the possibility of screening the electromagnetic induction between these large loops of circuit seems almost hopeless.

John B. Taylor: It is a source of considerable gratification to me to see the trend of these papers on the matter of transformer connections Y versus delta, because, while I am not prepared to say I always favor the Y connection, I have had occasion in past years to recommend Y connections when I found myself in a minority. Just now it looks as though the pendulum is swinging the other way, and it may be well to put in a word of caution lest the pendulum swing too far.

This question of Y and delta connection is not ever to be settled by argument, or ever to be finally settled, because both arrangements have advantages, and the conditions under which they are used have been and will be variable, so that for a given system the advantages might lie with one connection or the other, in the future the same as they have in the past.

I would like to say that there is always a lot of confusion in discussing this point, which confusion has not been altogether absent in this discussion this morning; in other words, Y connection does not inherently mean grounded neutral. You can keep just as clear from the grounded neutral with the Y connection as you can with delta connection, so if you prefer to build your transformers with one or both parts connected in star, because of safe requirements, do not let the bugaboo of the currents in the earth keep you from doing it. There may be an advantage in tying to the earth at one or more points, but if it seem desirable to keep clear of the earth, that need not be the controlling factor in the connection of the transformer. This point always seems to be in evidence in a discussion of this subject and accounts for much of the discussion being altogether at cross purposes.

Mr. Blume draws some conclusions in his paper, and I am able to agree with all of these except the seventh, in which he

says, "it is necessary to solidly ground the neutrals at both receiving and generating ends of transmission lines." In my opinion the word "both" is open to exception. In general, the objections which may arise from grounding the neutral result from grounding at more than one point. Many of the advantages of the grounded neutral are perfectly well secured with the single ground, and many of the disadvantages are thereby avoided. Speaking in very general terms, I am inclined, with extra high-voltage work, to favor Y connections with the neutral grounded at one point only, and that is at the generating station. The case of the Pacific Gas & Electric Company is peculiar in that it has an extensive network, and there is no one generating station as the logical point for grounding.

Mr. Fortescue refers to the possibilities of taking full advantage in saving insulation material with the Y connection. The transformer designed with the minimum amount of material to go on a Y-connected system, with grounded neutral, might have practically no insulation at one end and full line insulation at the other end of the winding. With this form of construction it would not be possible to make the usual factory test of two or more times high potential for a minute. Some means might be devised to satisfy the customer that the transformer is all right in spite of its inability to stand the customary high potential test.

As to the paper dealing with the Pacific Gas & Electric Company system, Mr. Osborne has covered the principal points relating to telegraph and telephone matters which I intended to make, and I can pass in the interest of saving time.

The contribution of Mr. Semenza refers to the Societe Conti transmission as causing telephone and telegraph troubles. I happen to be familiar with that particular case, and there, again, the trouble is due to grounding at more than one point, returning a considerable current of triple frequency through the earth, with accompanying induction in neighboring telegraph and telephone lines. Earth currents should be avoided in laying out a-c. systems.

Mr. Lewis has given an interesting summary of the connections in different plants in this country and other parts of the world. This table probably represents the opinions of manufacturing engineers, quite as much as the opinions of the operating company engineers. That this table shows the Y connections to be on the increase is worthy of notice.

The series of curves and the demonstrations Mr. Montsinger has made are an interesting example of what we may sometimes do with waste products. By-products sometimes come to be of more value than the original article of manufacture. The ability to obtain triple frequency from static transformers is, just at the present time, little more than an interesting plaything,

and its value will probably be worked out in the laboratory rather than in the commercial field. The objection to the low power factor and limited output relative to the size and cost of the apparatus, would seem to work against this being a satisfactory scheme of power transmission, though it is certainly a great convenience if you have three-phase 60-cycle current at hand to connect three static transformers, push up the density and obtain a limited supply of current at 180 cycles. Some years ago I amused myself by operating an arc lamp at 180 cycles, which, on 60 cycles, flickered objectionably. There are possibilities that a 25-cycle system might use a limited supply at 75 cycles, where the 25-cycle flicker is objectionable. These appear interesting and special applications rather than possibilities of power transmission.

In England a Mr. Taylor has been advocating this frequency change, and I believe seriously proposed the use of it on 25-cycle railroads. As this would involve three-phase generators at 8⅓ cycles, the costs and difficulties of obtaining 25 cycles in this case would appear to be much greater than the difficulties now holding for direct generation at 25 cycles, single-phase.

F. C. Green: For convenience in the discussion of this subject, the transmission system is divided into two parts: the transmission line, including high-tension switches and lightning arresters; the transformers connected to the line. Two classes of troubles are experienced with the transmission system; one affects the line and the other affects the transformers. High phase-voltages cause flash-overs of insulators, damaging the line; frequently burning off the wires and breaking the insulators. On the other hand, practically no troubles have been experienced with transformers on account of high phase-voltage. In almost every instance the trouble has been due to high frequency produced by disturbances in the line. This division into two parts seems to be a natural one.

There are many points of minor importance to the main subject, and I agree with Mr. Taylor that a great deal of the work done on the papers and a great deal of the discussion has been spent on these minor phases, such as the triple frequency and its effects. So far as abnormal voltages are concerned, or dangerously heavy currents, the triple frequency does not need any further study because, as was pointed out yesterday, these effects can be entirely eliminated by a number of methods. If, however, for any reason it should be desirable to use a system of connections which would involve triple-frequency effects, they can be eliminated as pointed out by Mr. Fortescue, in either interconnecting the phase windings, or in the interlinkage of the flux, as in the three-phase, core type transformer. But, so far as can be seen, there is no reason for using such a system of connections, because the grounded Y-delta system eliminates all of these objectionable effects.

Another minor point that is brought out in the papers bears upon electromagnetic stresses. That is a question which manufacturers particularly, and in a limited sense, operators, have been very seriously interested in. But when we study into the situation, we find that troubles resulting from electromagnetic stresses have been confined to those systems which have as their basis large turbine-driven generators feeding into underground distributing systems, and in a lesser extent, to small transformers taking power from large capacity substations. In these installations, troubles have been experienced from electromagnetic stresses, but in overhead transmission systems no troubles of consequence have been experienced. That is, the volume of these troubles is so small as to make them negligible in overhead transmission systems.

The one point that, it has seemed to me, has the greatest bearing upon the whole question, has not been treated at all in any of the papers. Perhaps we may say that a very good foundation has been laid in the papers for building up a discussion on this vital point, but all of the papers are devoted to normal frequency effects. The grounded Y-delta is clearly shown to give much lower phase-voltage stresses than the delta-delta under abnormal system conditions.

With the isolated delta, in case of arcing from line to ground, observation convinces me that not only phase stresses are much greater, but also high-frequency stresses which cause transformers to break down between coils. In this particular feature lies the most vital part of the question. With the neutral grounded, arcing from line to ground is more steady than arcing in the isolated delta system. With the grounded neutral, there is a dynamic voltage across the arc, while with the isolated delta, the voltage from line to ground practically disappears upon the establishment of the arc. Under this condition, the making and breaking of the arc occurs more frequently. Since high frequency occurs only at instants of making and breaking and not during existence of arc, it is evident that the system of connections resulting in fewer makings and breakings of the arc, is the safer.

In one of the papers the point is made that for systems of 33,000 volts and below, the isolated delta system is more desirable because it is more flexible. If it is true that under arcing from line to ground in the isolated delta system, there are more repetitions of high-frequency strains, the argument advanced in favor of the isolated delta system for 33,000 volts and below, does not hold, for the reason that an arcing ground in a system of 33,000 volts or lower would have the same tendency to produce high frequency and to cause the transformer to break down.

It is understood in this discussion that only the high-tension side of the transformers is connected in Y, and that the neutral of the Y is solidly grounded. Various other Y connections that have been enumerated are practically eliminated without discussion.

The possible use of two transformers in the delta system is advanced as an argument in favor of that system. Two transformers may be used with the grounded Y system, but not to the same extent as two transformers with the delta system; so that, even in this respect, the advantage is based upon degree rather than upon the nature of the system. The point has already been made of the great advantage in lowering the cost of transformers by having them designed for the grounded Y connection.

Another vital point in considering these two systems is the fact that with the grounded Y the location of a fault in the system is easy. Those who are familiar with the operation of plants know the importance of being able to locate troubles easily.

Mention has been made of the advantage in the delta system that one line wire can be grounded and the system continue in operation. I believe it is generally agreed that this applies only to short systems, or systems of low voltage.

P. M. Lincoln: This question of grounded neutral versus an ungrounded neutral is one which, I have always maintained, it is impossible for any man to sit down with a pad of paper and slide rule and figure out which way it should go. I think that this question is one of those which must be settled by experience, which must be settled by the man in the field, and for that reason I am very glad to read the paper by Messrs. Jollyman, Downing and Baum. I believe that the testimony of these gentlemen, operating men as they are, is of much more value and can be given greater credence than the testimony of those who simply sit down and look at this thing from the standpoint of the designing engineer. I think that it is a question which must be settled by practise rather than by the designer.

D. W. Roper: Mr. Fortescue in his paper makes a statement as follows: "In four-wire three-phase systems, where the e.m.f. is stepped up through the delta-star transformers, and three-phase power is supplied through star-delta step-down transformers, the latter, if their neutral is connected to the neutral, serve as balancers for loads taken off between neutral wires and lines." That statement is quite correct, but it gives a very bad operating condition. It is much easier to obtain balanced voltage in other ways, by regulators on the individual phase wires, if regulation of voltage is desired.

Further, if you have a three-wire transformer bank of that kind with a transformer neutral connected to the system neutral, the blowing of the fuse on one of the transformers does not interrupt the customer's service, and is likely to result in a burn-out of the other two transformers due to their overloading.

In Chicago both methods of operation have been tried. The scheme of grounding the transformer neutral to the system neutral was tried at first, but there were so many cases of trouble of that kind that the scheme was abandoned and the practise

is now universal, of connecting the three transformers for a power customer in star but leaving the neutral of the transformers entirely free from the neutral of the system.

One of the papers makes some reference to arcing grounds on a grounded neutral system, stating that they are, perhaps, not impossible, but are very rare. The system in Chicago, a four-wire, three-phase system with grounded neutral, has had a number of cases where an arcing ground has occurred and caused some disturbance. None of these have been very serious, but it is desired to call attention to the fact that such combinations were quite possible. An example may illustrate the point. A circuit operating normally, suddenly had the switch opened automatically in the station. It was tried several times, in succession, and each time it again opened automatically. A few minutes later we heard that an auto truck ran into and broke down a pole and that the primary wires had fallen down into the street. Trouble men were sent to this location to clear up the local trouble and the circuit switch was again tried and again opened automatically. Further examination disclosed the fact that a lightning arrester had broken down some distance away, say half a mile, from the scene of the place where the wires were down, and this lightning arrester trouble was undoubtedly caused by the high-frequency and high-potential disturbance due to the wires being down in the street at the first location.

F. W. Peek, Jr.: I would like to call attention to a point which, it seems to me, is a most important one, and which has been overlooked in this whole discussion. I do not believe that the success of the transmission of energy electrically depends on whether the transformers are either Y or delta connected. We have actual practical demonstration of successful transmission with both systems. Troubles do not generally *originate* due to the energy of the transmission system, but to energy external to the system impressed somewhere on the transmission line. In most cases the transmission lines are very long and there is probably not a lightning arrester within many miles of where the trouble starts. Insulators arc over. The energy of the system then enters, and adds to the trouble, as over-voltage or over-current, or both. Damage to apparatus may be due to lightning directly, or to the transient voltages or short-circuit current of the system energy following the lightning discharge.

Laying aside, for the moment, the relative merits of one system or the other, the most important point in transmission, and the one that I wish to emphasize, is the insulation of the transmission line. The transmission line should be insulated just as well as is economically possible, in order not to make lightning arresters of the insulators. When insulators arc over, the result is a short circuit or an "arcing ground." The arc is not under control. The line insulation should be such that the lightning arrester has a chance to discharge. The arc is

then under control and is suppressed before appreciable damage results.

There are many inconsistencies in the way in which transmission lines are insulated. I will take an actual line as an example. In a certain part of the country where the lightning is very severe there are two independent lines along the same right of way. One line is operated at 22,000 volts, and this has two suspension insulator disks in series, or operates at 11,000 volts per disk in terms of line voltage. The other line is a 100,000-volt line and has five disks, or 20,000 volts per disk in terms of line voltage. According to the general method of reasoning, the factor of safety of the low-voltage line is twice that of the high-voltage line (assuming good insulators). This is so in terms of the normal 60-cycle voltage, but it is not the normal voltage which starts the trouble. It is lightning. The arc-over voltages of the insulators on these lines are probably 160 kv. and 320 kv. respectively, while the puncture voltages are about 35 per cent higher. There was great surprise that all the trouble was on the low-tension 22,000-volt line, although it had a higher "factor of safety." Transient voltages induced on these lines by lightning probably range from 200,000 to 400,000 volts, with occasional voltages above the maximum of the range, and the majority below the minimum. Both lines are subjected to the same lightning voltage. The low-voltage line has practically no factor of safety in terms of the lightning voltage, as this abnormal voltage is often above 200 kv. The puncture voltage (about 420 kv.) of the higher-voltage line, except in rare instances, is greater than the lightning voltage generally induced upon the line. The factor of safety, as ordinarily expressed, has very little bearing as an indication of probable failure. In the case cited the "factor of safety" was seven on the low-voltage line and three on the high-voltage line. Either line would have operated equally well in a country free from lightning, as in California. The "factor of safety" should be much higher for low-voltage lines than for high-voltage lines when such lines are subjected to lightning. Of course, it is important to determine how far the insulation shall be carried out and what the factor of safety shall be. I have noticed in certain sections of the country, where lightning troubles are very severe, that when more than four or five disks are used in series there is very little trouble from lightning. Where a smaller number of disks are used the troubles are greater. Of course this also applies to pin type insulators, the number of disks merely indicating the value of the insulation. Line troubles decrease as the insulation is increased because the insulation breakdown voltage approaches or becomes greater than the induced lightning voltage. Arcing takes place over the arrester where it may be suppressed. Great damage is done by arcing following a lightning stroke.

The effect of the initial lightning stroke will be practically

the same with either delta or Y connection. The after effects due to arcing, etc., will, however, be different. In selecting insulators the mechanical side should not be lost sight of. Insulators may pass electrical tests very well, but develop small cracks when put in service, due to poor mechanical design. Failure occurs due to ordinary line surges. It is often, then, assumed that high voltages exist when, in reality, the insulators have become bad.

Great caution is necessary in making a diagnosis of a failure in apparatus, as transformers. Failures have often been attributed to over-voltage which were really due to the mechanical strains of over-current. Such failures may take place at the first slight over-voltage because the insulation has first been damaged mechanically by over-current. Mistakes in the opposite direction are also easily made.

It is not my intention to go far into the relative merits of either system. Either system may be a success with proper line insulation and proper operation and inspection. The choice depends a great deal upon whether there are a number of power houses and a network, or only one power house, whether reliability of service is the all-important factor and can be paid for, etc. This is especially so at low and moderate voltages, where the delta system is most often desirable on account of its greater flexibility and reliability. At very high voltages and with very long lines the advantages of the delta are lost somewhat and the grounded Y may be used. For instance, under these conditions the charging current and corona current with one line grounded may approach short-circuit current. An accidental ground on such an isolated delta system may thus cause large current to flow. This large leading current flowing through a reactance will cause abnormal voltage. The cost of the apparatus may have a bearing in favor of the grounded Y at very high voltages.

When comparisons are made of different systems in different parts of the country, to determine the relative advantages of delta or grounded Y, "shut-down" data should always be given, otherwise comparisons are almost valueless. A statement of satisfactory operation is not sufficient, as the term has decidedly not always the same meaning.

J. R. Werth: I should like to have Mr. Fortescue in summing up his paper, advise us in regard to his tabulation where he says "Y grounded direct or through resistance." I should like to know whether he has any data indicating whether any of these systems are grounded through a reactance; in other words, has the reference to the reactance been omitted because none of these systems was operated, or has it been omitted simply because he considered it not pertinent to the discussion?

Louis F. Blume: In reply to Mr. Taylor's objections to the complete association of the delta-Y connection with the grounded system, I believe that this has been inadvertently done through the emphasis on the discussion of grounded vs. isolated systems.

Obviously a grounded system must be delta-Y and a delta-delta system must be operated ungrounded. From this have arisen two questions:

1. Grounded systems vs. isolated systems.
2. In isolated systems the delta-delta connection vs. delta-Y connection.

As by far the larger number of delta-Y installations are operating with grounded neutral, and also as the first of the above questions possesses the greater importance, the term delta-Y has come to denote a grounded system.

Mr. Taylor objects also to my conclusion that "If it is desired to limit the value of potential at fundamental frequencies above ground of any part of the system to 57 per cent of line potential, it is necessary to solidly ground the neutrals at both receiving and generating ends of transmission line." I am perfectly willing to remove the word "both" in the above statement provided it is applied only to transmission lines in which the kv-a. capacity of the step-down transformer groups is practically equal to the kilovolt-amperes capacity of the step-up transformer groups, but if the step-down units are small compared with the size of the step-up units, and particularly if the step-down units are scattered over considerable territory, which is the case when a generating system is supplying power by means of a large number of feeders, it will be necessary to solidly ground the neutrals at both ends if potential stresses at fundamental frequencies are to be limited to 57 per cent of line voltage.

Mr. Semenza and Mr. Osborne have both spoken of the effect on the operation of telegraph and telephone lines of operating systems with neutral grounded. Under normal conditions of operation there is no difference between a delta-Y grounded system and an isolated delta system as far as the effect on telephone and telegraph lines is concerned, unless the grounded system carries an unbalanced load between line and ground. The latter case constitutes a four-wire system in which telephone troubles are caused by unbalanced loads. Obviously, troubles from this cause should not be given as an objection to the operation of transmission lines with grounded neutral, but should be considered only as a valid objection to the loading of three-phase systems from line to ground.

Telephone and telegraph interference resulting from third-harmonic current flowing in the ground under certain conditions of transformer operation should not be considered an objection to the grounded Y system, because, as Mr. F. C. Green has pointed out, in all properly designed transformer connections such troubles are entirely eliminated.

Mr. Peek has raised a number of interesting questions, and intimates that there can be potential disturbances on grounded systems, and also current disturbances on isolated systems. Undoubtedly this is true, and it is to be regretted that more

definite information concerning this feature has not been presented.

In general, I agree with the various members who have said that the papers as presented do not completely cover the question under discussion. There are a number of troubles which occur on transmission lines which have a very vital bearing upon the question, and which have only been casually mentioned. On this account it is very difficult for us at the present time to form any definite conclusions as to the relative superiority of either system.

C. L. Fortescue: In closing the discussion on my paper, it seems necessary only to sum up what has been said by previous speakers, since most of the questions asked by certain speakers have been answered by others.

However, I will first touch on the papers by some of the other authors, which deal with questions treated in my paper. In the paper by Messrs. Sorensen and Newton, which was read yesterday, tests were made on Y and delta connections, and some very radical conclusions were drawn. I may state that I have gone over these tables carefully, and find no basis for these conclusions. I notice that many necessary data are missing. There is no information as to the primary voltage and the secondary voltage of the transformers, the type of generator, how it was driven, and we do not know whether the iron in the transformers was saturated or at normal induction, in other words, we have nothing in this paper to enable us to draw our own conclusions.

The authors' conclusions are, I might say, somewhat dogmatic. In one paragraph this statement is made:

"When transformers were made in small sizes only, particularly if they were shell type, there was some advantage in having the windings connected Y for the high-tension side of the bank, as this allowed a smaller number of coils and less insulation, because the normal strain was 57.7 per cent of that of delta-connected transformers. The increase in size of units and the provision for maximum strain where one line becomes grounded have made these economic advantages obsolescent, except in some very special cases of small, high-voltage units. Hence, from the point of design and manufacture, there is no advantage for either Y or delta construction."

This is puzzling. I feel that I cannot agree with this statement. I think, now that we are getting higher voltages, even such a little difference as a normal potential stress of 57.7 per cent of line voltage as against 87 per cent, becomes of more and more importance.

There is one point in Mr. Blume's paper that I would like to call attention to, namely the question of operating delta banks in multiple with open delta banks. Mr. Blume says that when two or more delta banks are operated with an open delta bank, the total capacity is somewhat lower, but that by inserting

reactance in series with the remaining phase the capacity would be considerably increased. The better way of operating such banks in multiple would be to insert reactance coils equal to the effective reactance of one transformer in the apex of each of the open delta banks. This produces in an open delta the same effect as a balanced delta connection. The banks will then divide the load as if all the systems were balanced. By inserting the proper impedance in each line of the remaining banks the delta-connected banks may be operated at full capacity without overloading the open-delta-connected banks.

In regard to the discussion on my paper, Mr. Taylor has pointed out that there is some confusion as to the manner of operating delta-delta and delta-star-connected banks of transformers. There seems to be an impression in the minds of a great many of the people who have discussed this matter that delta-star-connected banks necessitate grounded neutral. I want to emphasize what Mr. Taylor has already said, namely, that the delta-star can be operated just as well without the grounded neutral, and it also has some other decided advantages which have been sufficiently dealt with in my paper. The points which Mr. Green intimated had not been touched on are also referred to in the paper.

The characteristics of the transmission lines and local conditions, as Mr. Peek has brought out, are the predominating influences, so that in some cases in the delta connection the troubles are current troubles as against the usual voltage troubles, and in some cases in the Y connection the troubles are voltage troubles as against current troubles.

In connection with telephone troubles in grounded systems, the delta-star step-up transformer almost entirely eliminates the third harmonic. It does not eliminate it entirely, because of the drop through the effective primary impedance, due to the magnetizing current, which has harmonics of the third group. This produces a small third-harmonic pulsation in the neutral, which may have an amplitude of the order of ½ per cent, or less, of the line voltage, but is not of sufficient magnitude usually to produce telephone troubles.

I think, as Mr. Blume has pointed out, that the telephone troubles in star systems have been due largely to Y-Y-connected systems in which the neutral of the Y is connected with the neutral of the generator. The generator nearly always has a triple-harmonic component in the voltage between neutral and line, which is transformed in the secondary, and the charging current to ground due to this component even when small may be extremely large, as has been pointed out in the discussion, and cause telephone troubles. Also it is a very common practise, at least in the West, in sparsely populated districts, to load between one wire and ground, which is also very bad practise as far as telephone circuits are concerned.

To sum up, it seems that sufficient regard has not been paid

to the advantages of the delta-Y system ungrounded as against the delta-delta system. It has decided advantages, which should be given consideration. In fact, the higher the voltage, the greater are the resulting advantages. In my paper I have stated that, if the voltage is above 44,000, generally speaking, the star connection grounded or ungrounded has the advantage.

There was a question asked as to the use of reactance in series with the neutral to limit the short-circuit current. I have no data as to whether any of these systems mentioned use reactances or not. About seven or eight years ago, a system came under my observation in which the neutral point of a star-connected auto-transformer was to be grounded. The neutral point was first of all solidly grounded, which resulted in considerable disturbance in neighboring telephone circuits. Grounding through reactance was next tried and much to the surprise of the experimenters the disturbance was increased; the more reactance they put in, the more charging current they obtained. I rather think that a reactance is not the proper thing through which to ground the neutral point.

I think Mr. Roper made the statement that it was inadvisable to connect the neutral point of star-delta step-down transformers to the neutral wire in the four-wire system. Generally, the four-wire system is operated from the generator, and since a triple harmonic is usually present between the neutral wire and the lines, if the neutrals of generator and transformer bank are connected through this wire a third harmonic will circulate, which is a bad feature. "In four-wire three-phase systems, where the e.m.f. is stepped up through delta-star transformers and three-phase power is supplied through star-delta step-down transformers, the latter, if their neutral be connected to the neutral wire, serve as balancers for loads taken off between neutral wires and lines." The delta-star bank of step-up transformers eliminates the third harmonic, and permits the breaker to open when there is a ground or short circuit on the customer's line.

Max H. Collbohm (by letter): The papers presented, discussing the relative merits of grounded and ungrounded transmission systems, seem to be quite generally in favor of the grounded system, both from the standpoint of safety to equipment and convenience of operation. The writer's experience with a number of grounded and ungrounded transmission systems has prompted him likewise to give preference to the grounded system, provided certain precautions are taken to guard against service interruptions in case of an accidental ground on the line which ordinarily would cause a short circuit on one phase and open the line switch.

In a recent article* the writer discussed a scheme for protecting a grounded system against service interruption, which consists of a metallic grounding rheostat between the transformer neutral

*"Service Continuity in Grounded Transmission Systems." Max H. Collbohm, *Electrical World*, April 18, 1914.

and ground for reducing the current through the ground, and a special instantaneous circuit-opening relay inserted in the tripping circuit of the line switches and energized from the secondary of a current transformer, the primary of which is connected in the lead from the grounding rheostat to ground. Through this arrangement an automatic opening of the line switches by an accidental ground on the line is prevented, as the special circuit-opening relay energized by the ground current opens the tripping circuit of the line switches before the inverse-time overload relays of the line switches have closed their contacts. An ammeter, alarm bell and signal lamp inform the attendant of the existence and severity of the ground and permit him to isolate the line in trouble without service interruption.

The article mentioned gives a description of other protective features as well, and records also the actual operating results obtained during the lightning season of 1913 in the system of the Peninsular Power Co., Iron Mountain, Mich. (66,000 volts, 40 miles) which had been equipped with the protective equipment described in said article. As will be noted, the system went through nineteen lightning storms of more or less severity with only four seconds of interruption due to lightning, or practically none at all. It is a significant fact that not even a single insulator became damaged by lightning in spite of a large number of accidental grounds over them, which fact is evidently due to the installation of upper and lower arcing rods on each string of insulators.

These results seem to indicate that practically absolute continuity of service can be maintained in a grounded system, if properly equipped, with perfect safety to the equipment and convenience of operation.

Presented at the 296th Meeting of the American Institute of Electrical Engineers, Pittsfield, Mass., May 29, 1914.

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RELATIVE MERITS OF Y AND DELTA CONNECTION FOR ALTERNATORS

BY T. S. EDEN

ABSTRACT OF PAPER

The main advantages obtained with the Y connection are as follows:

(1) It is possible to bring out a lead from the neutral point of the winding, which is useful for various purposes.

(2) The cost is less than with the delta connection, requiring approximately 58 per cent of the turns.

(3) It is not possible for circulating currents of triple frequency to flow in the windings.

The delta connection does not appear to have any advantages except as a convenience in design for certain voltages. When used, proper precautions must be exercised in the design to eliminate excessive circulating currents.

THE FLEXIBILITY in design of three-phase machines, as compared with two-phase, lies in the possibility of using either the Y or delta connection.

It might be expected that either connection would be used indiscriminately, depending on which worked out best for the case in hand.

However, it is probably safe to say that over ninety per cent of the three-phase generators built are Y-connected.

The other cases are those in which, due to limitations in design as regards specified output, voltage, etc., the delta connection permits the use of standard frames and tools, thus avoiding development. A few cases will also arise where customer's specifications call for the delta connection.

Some of the advantages of the Y connection are as follows:

(1) The possibility of bringing out a lead for various uses from the neutral of the winding.

This lead may be grounded. It may be used as the return in a four-wire system, giving, with a 240-volt generator, the voltage between the neutral and the end of each phase for incandescent lighting; similarly, on a 4000-volt generator, giving 2300 volts for use with standard transformers for three-phase four-wire

systems of distribution. In this latter case the neutral is generally grounded. This system is used in many large cities.

(2) The Y connection gives the required voltage with 58 per cent of the turns required by the delta connection. This is a large factor in cost, especially in machines of high voltage and large numbers of turns per coil, where the expense of internal insulation increases rapidly.

(3) In a Y-connected machine, with ungrounded neutral, it is impossible for currents of triple frequency or multiples of triple frequency to flow, since the third harmonics, existing in the two legs of the Y winding which are in series between a pair of terminals, are opposed to each other and of equal value, thus neutralizing one another.

In a delta-connected machine, the triple harmonics are in phase with each other, and will send triple-frequency currents through the three phases in series of the closed delta. These currents are internal in the windings, the e.m.f. which causes them to flow being short-circuited in the closed delta, not appearing in the e.m.f. measured between terminals.

These circulating currents may be of great magnitude, entailing large I^2R losses in the windings and corresponding loss of efficiency.

(4) In general, for the average alternator, the e.m.f. wave of the Y-connected winding is nearer a true sine than that of the delta-connected generator.

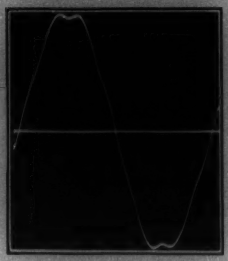
(5) The use of the grounded neutral reduces the potential strain on the insulation of the windings, permitting reduced thickness of insulation.

The above indicates the merits of the Y connection.

On the other hand, the delta connection does not appear to have any advantages. When used, care must be exercised in design, paying attention to the percentage of pole-face width to pole pitch, shape of pole face, saturation of the magnetic circuit, etc.

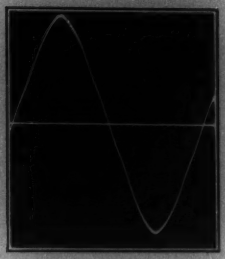
Fig. 1 gives the wave shape of the e.m.f. on closed delta of a 900-kv-a., 25-cycle, 400-volt unit, in which it was found that the circulating current at excitation for no-load full voltage was 83 per cent of full load current.

At 75, 87.5, 100 and 112.5 per cent of full voltage no-load, the circulating current was found to be 59, 69, 83 and 107 per cent, respectively, of full load current.



[EDEN]

FIG. 1—POTENTIAL WAVE OF 900-KV-A. 25-CYCLE, 400-VOLT GENERATOR, CLOSED " DELTA ".



[EDEN]

FIG. 2—POTENTIAL WAVE OF 900-KV-A., 25-CYCLE, 400-VOLT GENERATOR, OPEN " DELTA ".

[EDEN]

FIG. 3—POTENTIAL WAVE OF 7.5-KV-A., 60-CYCLE, 110-VOLT GENERATOR CLOSED " DELTA ".

[EDEN]

FIG. 4—POTENTIAL WAVE OF 7.5-KV-A., 60-CYCLE, 110-VOLT GENERATOR, OPEN " DELTA ".

[EDEN]

FIG. 5—POTENTIAL WAVE OF 7.5-KV-A., 60-CYCLE, 110-VOLT GENERATOR, ACROSS TERMINALS CONNECTED Y.

The analysis of this wave shape shows the equation of the curve to be

$$
\begin{aligned}
E = &+ 99.9 \sin(\alpha - 0.01 \text{ deg.}) \\
&+ 1.0 \sin(5\alpha + 36 \text{ deg.}) \\
&- 1.8 \sin(5\alpha + 4 \text{ deg.}) \\
&+ 2.9 \sin(7\alpha - 16 \text{ deg.}) \\
&+ 0.2 \sin(9\alpha + 59 \text{ deg.}) \\
&- 1.1 \sin(11\alpha + 72 \text{ deg.}) \\
&- 0.3 \sin(13\alpha - 45 \text{ deg.})
\end{aligned}
$$

Similarly, Fig. 2 shows the wave shape of e.m.f. taken across one leg of the delta, one corner of the delta being open.

The analysis of this curve gives the equation

$$
\begin{aligned}
E = &\ 99.9 \sin(\alpha - 0.1 \text{ deg.}) \\
&- 5.9 \sin(3\alpha - 9 \text{ deg.}) \\
&+ 0.3 \sin(5\alpha + 28 \text{ deg.}) \\
&- 0.1 \sin(7\alpha - 86 \text{ deg.}) \\
&+ 1.1 \sin(9\alpha + 8 \text{ deg.}) \\
&+ 0.1 \sin(11\alpha + 0 \text{ deg.}) \\
&+ \ \ 0 \sin(13\alpha + 0 \text{ deg.})
\end{aligned}
$$

In the former the percentage of third harmonic is small as compared with the latter, the e.m.f. being used up in overcoming the internal impedance of the machine. However, the fifth and seventh are strong, being produced by the pulsations of the field set up by the circulating current in the delta. The latter shows a third harmonic approximately 6 per cent of the fundamental, the others being practically negligible.

The Y connection constructed by adding two waves like Fig. 2, displacing them 60 deg., gives practically a sine curve. The use of a Y connection in this instance would have effected a saving of over 1 per cent in efficiency at full load.

Similarly, curves in Figs. 3, 4 and 5 show e.m.f. waves of closed delta, open delta and Y connection on a 7.5-kw. alternator in which the circulating current was a large percentage of full load current.

A further example of the effect of saturation on circulating current is seen in the following table, made up from tests of a 3000-kv-a., 6600-volt, 112-rev. per min., 60-cycle generator, connected delta for testing purposes.

Per Cent Full Volts per Phase	Circulating Current in Per Cent of Full Load Current
57	6
77	7.7
87	8
94	7.7
107	3
115	0

By using a 66⅔ per cent pitch winding, with the delta connection, the third and multiples of the third harmonic are eliminated. (See TRANS. A. I. E. E., Vol. 28 (1909) page 1064.)

Thus in a 2500-kv-a., 2300-volt, 133-rev. per min., 60-cycle generator delta-connected, using 66⅔ per cent pitch, an ammeter

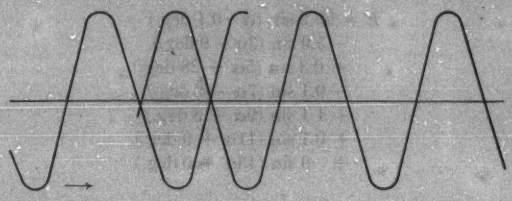


FIG. 6—POTENTIAL WAVE OF 2500-KV-A., 60-CYCLE, 2300-VOLT GENERATOR, OPEN DELTA.

in the corner of the delta gave no reading. The wave shape taken across one leg of the winding, with the delta open, is shown in Fig. 6.

It would therefore seem that from the standpoint of the designer, the Y connection is the safest to use and that great care must be exercised in using the delta connection.

Presented at the 296th meeting of the American Institute of Electrical Engineers, Pittsfield, Mass., May 29th, 1914.

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DELTA AND Y CONNECTIONS FOR RAILWAY TRANSMISSION AND DISTRIBUTION

BY CASSIUS M. DAVIS

ABSTRACT OF PAPER

Transformer connections under the following three conditions are discussed:

The railway (1) purchases power; (2) builds and operates the generating and transmission systems; (3)purchases power and in addition builds and operates a secondary transmission system.

The choice between delta and Y connection is frequently determined by purely economic considerations. However, it is common practise to use the delta connection on both the high- and low-tension sides of transformers, except in the case of six-phase converters, where the diametrical connection on the low-tension side is the rule. Synchronous converter substations employing two machines in series for high-voltage d-c. railways, are frequently operated from single banks of transformers, which have double windings on the low-tension sides. Methods of starting have little effect upon transformer connections except in the case of six-phase converters. Transformer connections are seldom important electrically in single-phase and three-phase railway systems. A secondary distribution system may at first be delta-connected and later changed over to Y connection to obtain better voltage regulation.

THERE are three general problems which present themselves for any railway system. They are classed as follows:

1. The railway purchases power.
2. The railway builds and operates the generating and transmission systems.
3. The railway purchases power and in addition builds and operates a secondary transmission system.

These conditions to a certain extent affect the choice of transformer connections, the use of delta or Y frequently being determined from purely economical standpoints. That is, it may be cheaper to install transformers with delta-connected primaries for a given synchronous converter than with Y-connected primaries.

A further condition, which may or may not have a bearing on the system of connection, is the fact that interurban lines and railway electrifications require substations which are spaced

at an ever-increasing distance from the generating station. They are frequently tapped off the same transmission line.

1. *Power Purchased by the Railway.* The railway has no choice as to the manner in which the supply system is connected. It must accept the power from either a delta- or a Y-connected transmission line, grounded or ungrounded.

General practise favors the delta connection on the high-tension side of the substation transformers regardless of the arrangement of the transmission system. The principal argument is that a three-phase bank of transformers may be operated open delta in emergencies at 58 per cent of its total normal output.

The connection on the low-tension side depends upon the type of distribution and on the kinds of transforming or converting apparatus.

For synchronous-converter substations with three-phase converters the delta connection is usual. This holds for machines of all voltages.

For synchronous-converter substations with six-phase converters the diametrical is the rule, since with either the double delta or the double Y, two secondary windings are required, while the diametrical connection needs but one secondary winding.

Synchronous-converter substations operating two machines in series for voltages from 1200 to 2400, and when supplied from single transformer banks, always have double secondaries connected delta for three-phase converters, and diametrical for six-phase machines.

Railway work seldom requires the neutral to be brought out. Where it is required, however, the Y, the "zig-zag" or the diametrical connection must be used, with proper provision for starting.

Motors for motor-generator sets may receive power from transformer secondaries connected either delta or Y. There is little choice between the two connections. Substations employing motor-generator sets frequently have a low-tension a-c. bus which is fed from transformers where the secondary connection is governed by conditions extraneous to railway operation. For example, the low-tension a-c. bus may form a part of an a-c. network, the neutral of which it is desirable to ground.

The methods of starting are controlled somewhat by the

secondary connection. Synchronous motors and converters are conveniently started from reduced voltage taps. If the transformers are delta-connected, starting can easily be accomplished on open delta. If they are Y-connected, the machines can be started at reduced Y voltage. With six-phase converters, the starting connections become very complicated with either the double delta or the double Y connection, especially with the machines of large output. Synchronous converters are seldom started by means of compensators for the reason that each converter is usually provided with its own bank of transformers, the taps of which are far less expensive than a separate compensator.

Starting from the d-c. side, or by means of a direct-connected starting motor, obviously has no bearing on the transformer connections and hence is omitted from this discussion.

The possibility of grounds and short circuits on the trolley or third rail has no effect upon the choice of transformer connections.

Since energy for single-phase railways is usually transmitted single-phase, the question of transformer connections does not come up for discussion. Even where the transmission is polyphase, the low-tension distribution for a single-phase railway system is taken from the transmission line through single-phase transformers. Thus, as far as the present discussion is concerned, there is no choice involved between delta and Y.

Either delta or Y connections may be used for three-phase railways. The choice would be governed by conditions existing in each individual case.

2. *Generating System Built and Operated by the Railway.* This problem involves the general question of delta versus Y connection. It is not necessary to go into a discussion of the advantages and disadvantages of either system since these points are brought out in other papers presented at this meeting. A railway load does not differ in essentials from any other load, and the same arguments relative to the choice of system apply here as well as to any other type of load.

In any system adopted, due provision should be made for extensions. This is especially true in railway electrifications where usually only a few miles constitute the initial electrification which ultimately may extend several hundred miles. Transmission lines for this type of load may be tapped at frequent intervals. This fact, it would seem, would tend to prevent,

or at least to mitigate, any tendency toward transmission line disturbances. Any high-frequency discharge or surge would be broken up in passing the various substations.

3. *Secondary Distribution Built and Operated by the Railway.* The railway frequently requires a secondary distribution system consisting of a line along the right-of-way. For moderate voltages, the line may be connected either delta or Y, with little choice between the two from an electrical viewpoint. It often may be advisable to economize on line material when first installed, and connect the transformers in delta until the load increases to such a point that better line efficiency and regulation are advantageous. Then the transformers can be connected Y for a 73 per cent increase of voltage. This of course necessitates transformers insulated for Y-connected circuits, and requires proper line insulators.

Conclusions

1. In general, the same arguments for delta and Y connections, as to reliability of operation, grounds, abnormal voltages, high-frequency disturbances, etc., apply as well to railway systems as to other systems and the factors which govern the choice of connection for one system govern the choice for all.

2. The low-tension sides of substation transformers are usually delta-connected, except for six-phase synchronous converters, and except where specific local conditions demand a Y connection for obtaining the neutral.

3. Six-phase synchronous converters are usually supplied from delta-diametrical-connected transformers. The Y-diametrical connection is also possible.

4. The choice of connection for low-tension distribution systems between substations is largely dependent upon commercial economy rather than upon purely electrical considerations.

DISCUSSION ON "RELATIVE MERITS OF Y AND DELTA CONNECTIONS FOR ALTERNATORS" (EDEN) AND "DELTA AND Y CONNECTIONS FOR RAILWAY TRANSMISSION AND DISTRIBUTION" (DAVIS), PITTSFIELD, MASS., MAY 29, 1914.

John B. Taylor: As Mr. Eden makes no mention of changing the construction which has been followed for a long while, from Y to delta, as he advances no argument for doing it, and as I do not think that anybody has good argument for doing it, it seems that the matter is fairly well settled. The discussions which have held so long on transformers have never come up on generators, and to that extent the work is standardized in part and in a more satisfactory state.

It does not seem that Mr. Davis has brought out anything that calls for much difference of opinion. It might be well to add that the Y-diametrical connection, the equivalent of Y-Y, has been used considerably. I believe Mr. Davis said he saw no reason why it was not permissible. He might have gone a bit farther than that, perhaps, and said it had been in use for a number of years without, so far as I am aware, any objection to its use.

There is this peculiar thing about the Y-diametrical connection which is also true of the Y-Y connection, that when the transformer is excited, before the load is connected, you may read unbalanced voltages on your three diameters, and furthermore, these voltages, whether or not unbalanced, may be more than the ratio of transformation calls for. I remember in the case of one of the early Y-diametric installations, in Waterbury, Conn., it was feared to start up the converter, because the voltmeter across the low-tension terminals showed values higher than the ratio of transformation allowed, although the primary voltage showed values it should have shown.

This was another instance of the third harmonic cropping up. Before the converter was connected they were measuring the t riple-frequency voltage combined with the normal, but the small magnetizing current which the converter readily supplied brought this down to zero.

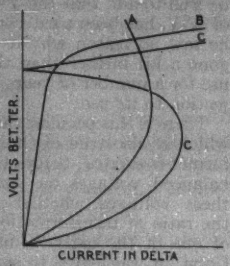
C. J. Fechheimer: Mr. Eden points out the advantages of the star connection for alternators, but does not bring out what may be the advantages of the delta connection. There are a few advantages, all of which have only limited applications, however.

The first is that with the delta connections we can secure half voltage very simply. For example, if a generator is wound for 240 volts, you can tap at the mid point on each leg of the delta for 120 volts. That is often convenient for lighting, and still permits the use of 240 volts for power. It is better than the star connection tapped at points between the neutral and terminals, to obtain nearly 120 volts. It is also better than 240 volts between terminals for star connection with neutral tapped,

thus giving 138 volts, which is frequently too high for lighting purposes.

The second limited advantage of delta connection applies in large machines wound for low voltages. For example, in a 2000-kv-a., 240-volt machine, the winding with star connection would be extremely difficult; it may be almost impossible. The delta connection lends itself far more readily, since it permits of more turns, the difficulty being to employ a reasonably large number of turns per phase.

The third limited advantage occurs when we endeavor to use existing parts, such as existing punchings, for a voltage for which the machine has not previously been wound, and it actually simplifies the connection rather than complicates it to use delta rather than star. For example, we may find for a certain voltage we want around $1\frac{3}{4}$ conductors per slot or equivalent thereof, for star connections. This would require 14 conductors per slot, 8 circuits, for a two-layer winding, or 7 conductors per slot, 4 circuits, for a single-layer winding. For delta connection we could use either 6 conductors, 2 circuit, or 3 conductors, 1 circuit, thus greatly simplifying the winding.



Mr. Eden shows in his oscillogram records, and in the subsequent analysis of the waves, how the delta current may vary. This refers to one or two examples, and does not cover the many cases which may arise. There is, possibly, nothing so erratic as the circulating current in the delta in the alternator. In some cases the delta current may be a curve like that shown as "A." The most common form of delta current is somewhat similar to that of a saturation curve, although usually the knee is more marked, as in "B." I have known one case in which the current rose gradually, dropped to zero and then rapidly rose again as in "C". I shall not take the time to explain these peculiarities. Although I have not had opportunity to check experimentally, I believe that the curve of delta current in delta-connected transformers varies as much as in delta-connected alternators.

Mr. Eden shows how the delta current may be reduced, or practically eliminated, by using a $\frac{2}{3}$ pitch winding. I do not think that that is the only way in which it can be reduced. For example, by inserting a sufficient amount of impedance at the apices of the delta, and tapping these impedances at their mid points, one can greatly reduce the amount of circulating current. The same effect can be accomplished by the use of magnetic wedges in the machine, which increase the internal reactance. We can, by carefully proportioning the parts of the

magnetic circuit, (for example, by carefully designing the shapes of the pole shoes), also greatly reduce the amount of circulating current. In some cases it may be an actual hardship to use a $\frac{2}{3}$ pitch winding, because this means that a greater amount of copper must be used per slot than if the full pitch winding were employed, and for this there may not be sufficient slot space where existing parts are used.

I also want to point out that circulating current is subject to change with load and with power factor. The circulating current which is ordinarily measured is that which flows when there is no load on the machine, and as soon as we put a load on, the wave form is altered. At zero power factor one gets an entirely different wave than that which obtains at unity power factor. The distortion of the magnetic field unquestionably also distorts the electromotive force wave. That may introduce harmonics which were not present before, or, if present, were probably in the wave to a different degree, and may consequently materially alter the magnitude of the circulating current. Therefore, even though the circulating current was negligible at no load, it may not be negligible at full load, or vice versa. This is something that one must guard against in large machines as they are designed at present; that is, with poor regulation, and comparatively small air gaps, the flux distortion is much greater than it was in machines of some ten years ago, when they had close regulation, comparatively long air gaps, and the flux distortion was comparatively small. I think possibly that also in delta-connected transformers, the load and power factor may have some influence upon the circulating current. I have not given this much thought, and I suggest this in order that those who have been working on this line may investigate further.

The author calls attention to the effect of the circulating current upon efficiency. I want to point out that I do not think efficiency is nearly so important in this connection as temperature. Circulation current may introduce temperature rises, which may be of serious magnitude; especially would this be the case under load if the distortion of the flux were such as to cause a considerable circulating current. In such a machine, then, the only proper way that one could make an accurate temperature run would be to put full load on it.

E. G. Merrick: I would like to make a few remarks in connection with Mr. Eden's paper, with especial reference to turbo-alternators. Mr. Eden and Mr. Fechheimer pointed out that in the salient-pole machine, harmonics can be reduced very considerably by the proper proportioning of the pole faces. For the usual ratios of pole arc to pole pitch this gives a maximum gap at the pole tips which is about double the minimum gap. In the modern turbo-alternator, which is now usually built with a cylindrical rotor, we have a uniform air gap and the above result must be obtained in another way.

A fully distributed field winding, one which would correspond

to the winding of a direct-current armature, will produce a triangular magnetomotive force curve, the apex of which corresponds with the center of the pole. On the other hand an entirely concentrated winding will give a rectangular magnetomotive force curve.

It is evident that by proper proportioning of the wound and unwound portions of the pole pitch between these limits we we can get a magnetomotive force curve which approaches very closely to a sine wave.

Neglecting saturation, any harmonics which exist in the magnetomotive force curve will appear in the flux wave, and again, these harmonics will appear in the same way in the electromotive force curve, modified by their respective winding factors.

If the ideal rotor winding is obtained—viz., that in which the wound portion occupies two-thirds of the pole pitch, we will get practically a sine curve of m.m.f. and the third harmonic and its multiples will disappear. It is therefore usually possible to design the non-salient pole type of machine so that it can be connected either in delta or in star.

Mr. Fechheimer has just made a statement in regard to the third harmonic being influenced by the load. Tests on the non-salient pole type of machine do not, however, indicate such an effect. This is shown as follows: Measurements on a delta-connected machine under load indicate a certain current X in each line and a current Y in the delta, Y being greater than X on account of the additional current due to the third harmonic. At no-load and normal voltage we get a value Z for the circulating current in the closed delta and the combined currents X and Z will equal the above current Y. This would indicate that the value of the circulating current due to the third harmonic has not been changed appreciably by the load.

C. J. Fechheimer: How many machines was that carried out on?

E. G. Merrick: I have tried it on a number of different machines.

C. J. Fechheimer: What kind of load?

E. G. Merrick: On non-inductive load.

C. J. Fechheimer: That is contrary to my observations.

E. G. Merrick: In each instance the calculated results have come within the limits of error of reading.

C. J. Fechheimer: You must recognize the fact that the circulating current due to higher harmonics is not directly additive to the load current. I see you combine it in quadrature.

T. S. Eden: There is no question that by using a proper width of pole face, in per cent of pole pitch, the third harmonic can be avoided. The alternator, on the wave forms of which I made an investigation and reported the results in the paper, was one in which the percentage of pole face to pole pitch was only 52 per cent. Had this been $\frac{2}{3}$, the third harmonic current would have been largely eliminated, and there would not be any such value as 60 per cent in the fundamental.

R. E. Doherty: There is one point that just occurred to me in the way of an explanation of the discrepancy between the observations of Mr. Fechheimer and Mr. Merrick. Mr. Fechheimer says that he has noted no change in effect of the circulating current in the delta under load, and Mr. Merrick has noted that it has been appreciable. I wonder if the possible explanation is that since this change that Mr. Fechheimer pointed out is due to a change in relation of the center line of flux from the center line of the pole, whether the use of different proportions of minimum gap to maximum gap in the two machines on which this thing had been tried out does not account for the discrepancy in observations? In the machines Mr. Merrick has referred to, he has pointed out that the maximum gap was something like twice the minimum gap. I wonder if this relation holds in the machines Mr. Fechheimer referred to.

C. J. Fechheimer: It does not.

E. G. Merrick: The tests I referred to were on smooth, cylindrical rotors, turbo-alternators.

C. J. Fechheimer: If the armature reaction, even in the turbo-generator in which the winding on the rotor is distributed, were sufficient to distort the flux, I should think the effect of the circulating current would be altered in most cases by change in load. I have not made any observations myself on turbo-generators in this regard, so I am not able to speak from experience. I am only theorizing. The machines I had in mind were definite pole alternators, in which the minimum air gap was but little less than the maximum air gap. By minimum air gap, I mean the gap at the middle of the pole, and the maximum at the edges of the pole.

R. E. Doherty: The condition, as I see it, is due less to difference in armature reaction than the spread of the exciting coils, which increase in reluctance in one case from the center of the pole to the edge, this difference being greater where the ratio of minimum to maximum gap is large than where it is more nearly uniform. The distorting effect of armature reaction would shift the flux a great deal more in the uniform gap.

Cassius M. Davis: I wonder if there is not a simpler explanation for that. In the transformer the triple harmonic exists whether there is load or no load, and the triple harmonic exists in about the same magnitude. It is not so noticeable in its effect upon the wave shape at load because the load current is so much greater than the triple harmonic current. Leaving aside the effect of flux distortion, I wonder if the circulating current in the delta is not there all the time in about the same magnitude, whether there is a load or no load, but in measuring the voltage or taking an oscillogram across the phases, the wave appears smoother at the load, due to the reactance drop through the armature winding, while the triple harmonic may still exist there. This is analogous to the exciting current of a transformer, which stays about the same, regardless

of the load, and is too small to appear in an oscillogram taken across the terminals.

John B. Taylor: Bearing on circulating current losses in a delta-connected generator, I recall tests measuring directly the triple-frequency voltages in windings of a generator by connecting in Y and reading between common connection or "neutral" of generator and a true or stable neutral of transformer bank. These triple-frequency readings changed as normal frequency load on the generator was increased or decreased.

With a delta-connected generator, I suggest measurement by ammeter or oscillograph of the three currents (two in generator windings and one in external lead), at a corner of the delta. By this means, amount of circulating currents at different loads and excitations may be determined.

Selby Haar: I speak in defence of the delta connection from the operator's standpoint. As long as conditions are likely to arise in service which make it necessary to operate damaged but partly serviceable generators temporarily, we cannot spare the delta connection. Anyone who has been able to maintain three-phase service with two transformers connected in open delta will agree with this statement.

Mr. Eden reports 83 per cent of normal load current in one case. This current could be reduced to a harmless value by inserting reactances which preferably should exhibit a proportionally higher reactance to harmonics than to the fundamental of the current wave; in view of some present tendencies of design, the increased reactance at normal frequency would not be altogether undesirable. Each reactance would consist of an iron core wound with a coil of several turns, from the middle one of which a tap is brought out. Each corner of the delta is opened, and the two leads connected to the ends of a reactance coil, the tap being connected to the line. Suppose such a coil to have $2n$ turns, then the current at fundamental frequency in one group of n turns (on one side of the tap) is 120 degrees out of phase with the current in the other n turns, and the resultant magnetomotive force of both will equal In, taking I as the current per phase. The current of triple frequency, however, flows in the same direction and is of the same phase in both parts of the coil, so that at current I, the magnetomotive force is $2In$. Thus the reactance (below saturation of the iron) should be 6 times as great for the triple harmonic, and 18 times as great for the 9th harmonic as for the fundamental. Of course the saving realized by the smaller circulating current in the generator is partly offset by the iron and copper losses in the reactances.

Where there are no insulation difficulties on account of high voltages nor space restrictions (as to shape and sizes of reactances) to contend with, the three coils may be wound on one core. Now the odd harmonics in the wave of e.m.f. (or current)

may be divided into three groups of the orders $3a$, $6a-1$, and $6a+1$, where a is any positive integer. The resultant magnetomotive force of these three coils, when supplied with balanced three-phase currents at fundamental, $6a-1$, and $6a+1$ harmonic frequencies, is zero, while the three individual triple, ninefold, fifteenfold, etc., frequency, magnetomotive forces are in phase. Hence the impedance of such a device to all harmonics of order not a multiple of 3 would consist of resistance only. Since, as stated, all harmonics above the third were practically negligible, the effect of such a coil should be very marked in this case. It would be interesting, as a check on this conclusion, if Mr. Eden could supply an oscillogram of the circulating current in one of these machines; it should show only the $3a$ harmonics. We should not give up the delta connection simply because it is difficult to design a good delta-connected generator.

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THE EVOLUTION OF THE INSTITUTE AND OF ITS MEMBERS

President's Address

BY C. O. MAILLOUX

Introduction

THE constitution of this Institute prescribes that the president "shall deliver an address at the annual convention." The duty thereby assigned to the president becomes one of his last official ones, when the annual convention falls so near the end of the term of office, as it has in the last few years.

The realization of the approaching end of his term of office made one of my distinguished predecessors feel that his presidential address was a sort of "swan song." It is a cause for congratulation both to the Institute and to him that he has since then contributed several other very good "songs" which have received great applause both here and abroad; and his many friends and admirers all rejoice over the good prospects of his being heard from again, many, many times. The fact that so many of our past-presidents have retained a great interest in the affairs and welfare of the Institute, and have continued to work most loyally and zealously in its service, makes me feel that it would be misleading to ascribe a "valedictory" character to the president's address. I am very certainly not inclined to regard it, in my own case, as an incident of "leave-taking," since I feel the strongest desire and disposition to continue to serve the Institute to the best of my ability after I return to the ranks. I prefer to regard it in the light of a graduation-thesis, constituting one of the requirements for the "honorary degree" of "past-president."

The Development and Activity of the Institute

The wondrous activity of this Institute, the enormous amount and the magnificent quality of the work which it does each year, are so full of interest and so worthy of attention, that they would easily furnish both the pretext and the inspiration for an interest-

ing and instructive address. To one who, like myself, had the privilege of "enlisting" as one of the founders, and who holds the diploma of charter-member of this Institute, its growth, its expansion, its work, and its achievements have been, from the beginning, and still continue to be, sources of increasing wonder and astonishment. There is, in truth, reason for us to be proud, even to the degree of exultation, over the fact that the American Institute of Electrical Engineers, the youngest in the family of national engineering societies in the United States, has pushed its way to the very first place among them all, not alone in point of membership, but in respect to its subsidiary centers of activity, *i.e.*, its Sections and Branches; also, and more especially, in respect to the number and the character of the contributions to original knowledge of which it has been the depositary and the means of dissemination; also in respect to the important role which it has played and the great influence which it has exerted in the entire world, in connection with questions of electrical units and standards and other matters calling for international conference and agreement. There is still at least one other respect in which it need not fear, but could challenge, comparison, (even if the list also included the sister societies in the rest of the world), namely, the proportion of active workers, *i.e.*, the proportion of members who give material evidence of their interest in the work, welfare and development of the Institute by making sacrifices not only of time, but of money through their zeal in its service. So far as I know, there is no other engineering or scientific society in the world which has the good fortune to have at its disposal, fre of cost, the services of so many high-grade men.

This willingness and readiness to serve are evident in all the Sections and Branches of the Institute; and that is precisely what has made the plan of forming Sections and Branches so successful. It is in connection with the activities of the central body of the Institute, however, that the results of the devotion of our active members are most apparent and significant. Each month, men who hold most important positions gather at the Institute headquarters from all points, far and near—many of them coming a thousand miles, and some even a still longer distance—to attend meetings of directors and of committees. In general, the attendance at these meetings is surprisingly large. Frequently, there are many different committees holding meetings. Some of these meetings may begin a day or two before, and some may not be over until a day or two after "In-

stitute day." Very often, the committee works until a late hour in the evening, and, occasionally, it continues its work the next day. On at least two occasions, one of our most important committees, the Standards Committee, has been in session day and night for more than three days in succession.

The enthusiasm and the energy of these faithful and devoted workers, their evident desire to collaborate and cooperate to the highest advantage for the good of the cause, cannot fail to excite both wonder and admiration. The interesting and significant thing is that these men work with the same earnest attention and the same desire to produce substantial and useful results that they manifest in dealing with matters of most profound personal interest and importance. Not only is this high grade work done voluntarily, but the men literally pay for the privilege of doing it. The time and traveling expenses of some of these men amount to a large figure at the end of the year; and some of them have been serving the Institute, at that cost, for many years. Moreover, in many cases, notably in the case of chairmen and secretaries of committees, the work done at meetings is in reality only a small part of the total work done by them, which includes a great amount of correspondence. I have deemed it a duty to refer to the amount and the quality of the work that is done by the members without cost to the Institute, for two reasons: First, because the fact that there are so many devoted, earnest, faithful workers rendering such valuable services at more or less great personal sacrifice and expense may not be as well known to the membership at large and as much appreciated as it deserves to be; second, because I wish to pay a well deserved tribute of praise and to do honor to these men. It is a duty and it is also a great pleasure to me to pay a tribute of appreciation and of gratitude, here, for the Institute and for myself, to all these faithful, self-sacrificing workers, to whose zeal, loyalty, energy and generosity, the Institute is so much indebted for its success and for the reputation which it has achieved both here and abroad. It is precisely here, in my opinion, that we find the true explanation of the phenomenal growth and development of the Institute. It has often been remarked, by persons who are informed about the activities of the Institute, especially about the work of its important technical and special committees, that if the time and effort devoted to this work had to be paid for, even at bare cost, the Institute would need an enormous increase in revenue to carry it on. This is a modest

statement, however; it would be nearer the truth to say that the Institute obtains, without cost, more and better service than it could ever hope to procure for money.

The Evolution of the Institute

As members of the particular guild of technical specialists who are interested in, and dealing with, the applications of electricity, we all are more or less familiar with, and we all have reason to feel quite content over, what electricity has already done in improving existing facilities and in providing new ones for the world's work, and for the welfare, comfort, and happiness of its inhabitants. Nobody has had more frequent occasion or better cause than have the members of our guild, in the thirty years that have elapsed since its foundation, to realize and to appreciate the fact that we are living in an age of rapid evolution and of wondrous transformations. The fact is that the electrical engineer has played the leading parts in several of those transcendental, epoch-making developments in applied science, which have wrought so numerous and such radical and far-reaching changes in industry, commerce, trade, and even in the conditions of our daily life. Moreover, he is expected and he is preparing, to play an equally important part in many other new, forthcoming transformations of methods and facilities for promoting the progress of the world in the direction of higher civilization and greater benefits for mankind in general, through a more general and a better utilization of the sources of energy which nature has in reserve and which it will yield up to man as soon as he learns how to use them. Some of the electrical engineer's dreams of the past, that seemed, indeed, at the time, as fantastic and impossible of realization as fairy tales, have come true, and in a way which exemplifies the adage that "truth is stranger than fiction;" and he has kept on dreaming, of other, more wonderful, possibilities. Indeed, the realization of the supposed illusory dreams of the past, shows that he was more a clairvoyant than a dreamer.

The fact that our seemingly extravagant expectations have been so often realized in the past, justifies our having other extravagant expectations for the future. I think that we are entitled to say that the electrical engineer has been and that he is still a prophet as well as a minister of the world's progress.

The last century, sometimes characterized as the age of iron and steam, witnessed the great feats which the engineer accom-

plished with iron as a structural material and steam as a source of power. In the present century, steel is taking the place of iron, and electricity that of steam; and the engineering feats of the last century will pale into insignificance, when compared with the vastly greater engineering achievements and wonders which are to come, some of which are, in fact, already impending.

The great diversity in the subjects treated in the technical papers which have been presented before the Institute, in the last ten to fifteen years, shows that our field, instead of contracting and becoming more restricted, as it was feared at one time might happen, is enlarging rapidly, and in all directions. The opportunities for original research and experimentation, the chances of making discoveries, and inventions, and the openings for new specialties in technical work, are becoming more, instead of less, numerous and favorable. The general outlook is therefore encouraging. The prospects for the continuance of the growth and prosperity of our guild were never better, seemingly, than they are now.

Our success as a guild will be sure and complete, on condition, however, that we suffer no loss of cohesion or of solidarity as the result of increased specialization. We must bear in mind constantly that "in union there is strength." We must beware of segregation. This is a point of vital importance. There are delicate problems, here, for the Institute to solve.

The expansion of existing fields of activity or the advance into new ones, leads, very often, to the creation of new specialties. Some of these new specialties have assumed sufficient importance in the number of persons interested, and in the amount of technical work done by them, to attain to the dignity of substantially distinct branches of the engineering profession, for which separate technical societies have been created, like the American Electrochemical Society, and the Illuminating Engineering Society, the former of which is wholly and the latter partly a subdivision of the general field of electrical science and engineering. The subdivision of a large field into smaller independent or subsidiary fields of technical activity, may have been warranted in these two cases, but in other cases, where an attempt was made to follow their example, the results have been far less satisfactory; and it would have been better if, before founding new societies, the persons interested in new specialties had tried to utilize other facilities, including, especially, those which the Institute could offer them.

The technical committees of the Institute represent an honest and earnest effort which has been made—and with considerable success—to secure diversity in technical work and to give scope, individuality, and recognition to the various specialties and activities of the members or of groups of members of the Institute while avoiding their segregation into distinct small societies.

Each of our technical committees has the resources, the authority, and the prestige of the whole Institute; and every member of the Institute receives the full benefit of the activity and of the work done by the specialists constituting the committee. In effect, the result is the same as if every member belonged to a number of distinct societies specializing in certain subjects. This point is deserving of attention, as disclosing a feature which is not as well understood or as fully appreciated as it deserves, and as suggesting a field for further development.

So far as concerns the specialists themselves who take part in the activities of the technical committees, they are relieved of the responsibilities and burdens of keeping a small society alive to give scant support and limited publicity to their work as specialists. It is obvious that their work reaches a much larger number of people and does much more good when done under the auspices of the Institute. The Institute plan is based upon the principle that "in union there is strength," and on the economic advantages resulting from concentration of organization and administration. This plan fosters diversity by permitting activity in many directions that would not warrant the formation and could not maintain the existence of separate societies, and, for other specialties which could only hope to maintain a separate society on a small scale, and in a more or less precarious way, it offers a larger field and secures a larger audience, which, as we all know, is a consideration of the highest importance, because it gives the best incentive and is the best stimulus for doing work of the highest grade.

The preceding considerations reveal certain fundamental principles of efficiency and economy with which electrical engineers are all very familiar, namely, the importance of high values for the "diversity" and "load" factors in central stations. The Institute is, in effect, a kind of central station for the generation and distribution of a certain kind of electric "power" which is useful in the production of electrical "work" of greatly diversified character and of extreme importance, as a whole, to the vocation of the electrical engineer, and to the standing and the

advance of the electrical engineering profession. The analogy is perfect; centralization of activity and the superimposition of load-curves,—as the result of increasing the diversity-factor,—lead to a higher load-factor in the Institute, and in about the same way as in an ordinary electric power-station.

The Institute has abundantly realized its objects as we find them stated in the constitution, namely, "The advancement of the theory and practise of electrical engineering and of the allied arts and sciences, and the maintenance of high professional standing among its members." It has amply fulfilled its mission and its trust as the representative of the profession of electrical engineering in the broadest and most comprehensive sense. It gives shelter and support, encouragement and standing, to all the branches and specialties of the profession that are worthy. Its numerous Sections and Branches in North America, and its many groups of specialists working in various electrical fields, suggest a federation of states and territories, whose citizens are amalgamated into a coherent mass, in accordance with the old motto, "E pluribus unum," which the Institute exemplifies and glorifies.

In expressing my gratification over the good work done thus far by the Institute, nothing is farther from my thoughts than the wish to suggest or imply that there is not still more, indeed, very much more, good work ahead, waiting to be done. In truth, my feeling is that it would be very difficult to set any limits to the development of the Institute and its capacity for the further advancement and realization of its aims and objects. There will be no dearth of good opportunities in many directions; and I am confident also that there will be no lack of initiative, interest and effort on the part of the active members whose self-sacrificing devotion has done so much, as I have already indicated, to raise the Institute to its present high plane of efficiency. As time goes on, with better resources and riper experience, the Institute will be able to undertake tasks of greater magnitude and solve problems presenting greater difficulties than would have been possible hitherto.

There is one thought suggested by the foregoing sketch of the Institute's career which deserves to be impressed upon the minds of all its members. It is this: wherever in the extensive fields of electrical theory and practise a man may happen to be stationed, either by his own choice or by circumstances, whether he be genius or plodder, whether he be ambitious or modest, and

regardless of his specialty, or whether he have any specialty at all, there is room for him in these fields, there is a place for him in the Institute, and work for him to do, and there are benefits and honors waiting for him there. The Institute needs him, and he needs the Institute. Each can complement the other and can add to the other's "stature" in many ways.

Although the evolution of the Institute has been rapid, it has been, fortunately, also healthy. It has acquired a strong impetus which should carry it along steadily to ever wider scope and more fruitful influence. There is no reason why the Institute should not continue indefinitely to grow, to expand, and to increase its power for doing good to our profession and for developing a true professional spirit in its members. I trust that you all join me heartily in the wish that the Institute's career may be long and brilliant and I hope sincerely that you will all continue to do your best to help make the wish come true.

The Social and Civic Evolution of the Engineer

The preceding sketch of the evolution and development of this Institute has made it apparent that the particular branch of the engineering profession for which it stands before the world has attained a place of great distinction and high honor in that community of initiates and adepts known as the domain of applied science and technology and sometimes called the engineering world.

We might be content and satisfied to rest on our honors in that world, if it gave scope to all our aptitudes, if there were in it opportunities for the cultivation of all our faculties and the development of all our talents, and for the realization of all our ideals and aspirations. Unfortunately, that world is, after all, only a sort of technological workshop of vast proportions and of complex character, wherein one may develop great abilities and talents, it is true, but which aims at one thing only, the performance of scientific and engineering tasks and "stunts" of great commercial interest and industrial value to the whole world. It is not suited for the development of what we are wont to term the higher, better and finer side of human nature, including those important constituents of human character, built up of moral, ethical and spiritual attributes and of sterling qualities of mind and heart, those elements of general culture, high-mindedness and refinement, which breed the feeling and nurture the respect for ideals, and which develop those charms and graces of manner

that raise certain individuals to higher planes, and entitle them to greater respect and consideration than the rest, in human society.

I know that I need not dwell on the desirability of this kind of development, for I am sure that you all concede its necessity and its benefits for all classes of humanity. We all see quickly enough the "mote" that is in the eye of humanity in general; unfortunately, we do not always see the "beam" that is in our own eye, so great is the difference between looking at a thing in the abstract and in the concrete. That is what leads me to mention and to insist upon a point of great moment, not only to ourselves but to the whole world. It is this: we are further behind than we ought to be, in certain phases of that higher development which has just been alluded to; we are merely *followers*, whereas we ought to be *leaders*. I will admit that this condition has not been worse,—in many respects, it has, indeed, been far better,—in our branch than in the other branches of the engineering profession; but, the fact that we have been merely a little less blind to our opportunities and our duties than have our colleagues, is not an adequate excuse for our own delinquency. It is, perhaps, an accusation, as showing that, although more awake, we were not more alert or active.

One of the important objects which I have in mind, in this portion of my address, is to bring to the attention of electrical engineers,—and, incidentally, to the attention of all other engineers or classes of engineers who are "in the same boat,"—the fact that the acquirement of what might be termed "technical adeptness and dexterity," either individually or collectively, by the members of a profession, and the resulting increase of technical knowledge, accumulation of experience and data, and development of engineering methods, do not constitute the *summum bonum* of our professional life, and do not represent our only ideals or the sole end and purpose of our efforts, either in an individual or in a cooperative sense.

In extending and improving our relations to each other, through our Institute, we have laid the foundations for the development of a great guild. Let us remember, however, that in this case we ourselves may not, indeed, we cannot, be the sole judges of greatness. In reality, it is not *self*-recognition, but recognition of a class by *all other classes*, that counts. This is a point to which engineers as a class have given altogether too little attention. They have been too self-conscious

and self-centered; and they have not paid enough attention to their relations to the outside world. They have neglected to cultivate, and, consequently, they lack, the "*guild-spirit*"—that force which makes for the increase of prestige, influence and power of the guild, and secures for it the greater respect and consideration of other guilds and classes. It is high time that engineers should appreciate the importance of "taking their place in the procession", in a social, civil, and civic sense. While, in a professional class, the prominence of *individuals* may depend only or mainly on professional technique and achievements, the prominence, reputation or *caste* of the *class* or *clan*, as a whole, depends mostly, perhaps wholly, on the professional spirit—the "*esprit de corps*",—and on the ability of the guild or class to hold its own with the other guilds and classes, on common grounds, in social, civic ,political and other life, in the outer world. The next point of interest is that we really have duties to perform and are entitled to benefits, in that outer world. Moreover, our neglect to preempt or to occupy the place that belongs to us there, is a serious handicap to the prestige or influence of our particular professional class, and places it in a condition of relative disparity, before the world, as compared with other professional classes,—such as those of law, medicine, the fine arts, etc., which assert their rights and utilize their opportunities systematically.

When people speak of the "upper crust" of society, they imply and recognize, tacitly, the existence of lower layers, strata or classes in human society. It were indeed idle to deny the existence of classes, orders or groups in human society, any more than in the rest of nature. It seems to be in nature's general program. We find classes in the infinitely great worlds of the astronomer, and we find them in the infinitely small worlds of the bacteriologist, and in that of the physicist; and we find them everywhere between these two extremes, in the animal, vegetable and mineral kingdoms. An interesting example of the stratification of life was noted by the Prince of Monaco in his deep sea explorations. He found that the ocean had upper and lower "layers", or "tiers" of inhabitants, with an indefinitely great number of intermediate layers; moreover each kind of life, indeed each species of fish or animalcule, has its place at a certain depth, where it is "at home", and above or below which it is "out of its element", and may be so uncomfortable or so handicapped that it cannot live.

In this entire system of stratification in the universe, the relative location of each layer may be the result of accident or circumstances, but it is always liable to change. In the case of the "layers" of human society, some important changes have been effected rather suddenly by *revolution*; but most of the changes occur by the slower and better process of *evolution*. The important principle of the "survival of the fittest" is always in operation here, for there is continual battling by contending forces, the weak being crushed or thrust aside by the strong. The social or civic level occupied by any class in human society is at the point of balance or equilibrium between its own efforts to rise to higher levels and the efforts of other classes to prevent them from rising in order to take their place.

It is my opinion, as it is also that of many of my colleagues who have given careful thought to the matter, that as a professional class, we are entitled to occupy a higher station and to receive greater consideration and respect than have been accorded us by the public. I will not deny that we have made considerable progress in the direction of social respectability and higher civil status. A recent review of the evolution of the engineer, in the London *Times*, contains the interesting statement that "Considerably less than a hundred years ago engineers in the navy took rank *next below carpenters*". It is most gratifying to realize that, in the present day, in all the navies of the world, the engineer is in the "officer" class and that, at least in our navy, many of them have attained the "Admiral" class.

In an address on "the position of the engineer in civic and social life" presented before an Austrian technical society in 1877*, one finds ample evidence that the civil and social status of the engineer were then far from satisfactory to the engineers themselves. There is lament over the fact that the older professional classes, which had hitherto divided the world amongst themselves, looked upon engineers as "upstarts" and "intruders". We may still be considered "intruders" by the lawyers and politicians who fill the positions that we engineers alone are qualified to fill properly on public service, public works, and

* "Die Stellung der Techniker in staatlichen und socialen Leben." Vortrag des Herrn Hofrathes M.M. Freiherr von Weber. Gehalten am 17 Feb. 1877. Wochenschrift des Oesterreischischen Ingenieur und Architekten Vereins. Vol. II, Feb. 1877, pp. 59-60. Mar. pp. 85-88. (To be found in A. I. E. E. Library, Mailloux collection).

other commissions dealing mostly with engineering questions; but, at least, we are no longer called such harsh names. So we have made some progress,—just enough, perhaps, to show how far we are still from where we ought to be. The following passage in the address is well worth quoting: "Only in rare, exceptional cases, do we see engineers, even in matters of specifically technical character, vested with the authority which gives the ultimate final decision; indeed, they are never in the majority in the deciding body". Further on, in the same address the statement is made that the final deciding power in matters of the kind already mentioned remains "in the hands of laymen, and that the preponderating majority is composed of amateurs generally having a pronounced legal 'tinge".

These remarks, thirty-seven years old, need practically no revision for presentation before an American engineering society today. They still report the conditions quite correctly. The author calls attention to the fact that the civil and social status of the engineer are higher in France and in England than in the German countries. The engineer has never been regarded and treated in the former countries as an " upstart " or an "intruder". Of the French engineer, the paper says that his education not only equips him with the necessary knowledge and preparation for the fulfillment of all his technical duties, but that it makes him, in general culture, good breeding and social tone, equal to members of all other social classes, and that he is, therefore, received and acknowledged as such without any opposition. This passage is interesting as evidence of the benefits attainable from the kind of training which supplements technical adeptness and dexterity by the development of personal character along intellectual, cultural, social, civic and ethical lines. The article concludes as follows:

" Let us set aside small jealousies and controversies, let us help uplift each other reciprocally and in that way also raise ourselves in the estimation of the world,—let us stand fast, shoulder to shoulder, in healthy solidarity against the outside influences which begrudge us equality of privilege with the older professional classes, and which strive to shut us out;—let us show, by our own discipline, that we are qualified to advise, to direct, to lead, in the highest capacities, and let us be on all occasions gentlemen in disposition and deportment.

"The conquest of that position in civil and social life for which we are striving and which belongs of right to us, on the strength of our knowledge and ability, will then result without fail."

It would be difficult to improve upon this good advice even at this later date. The fact that it is still so good shows that it is

still needed; for the millenium expected thirty-seven years ago is not yet quite here.

This plea for the proper recognition of engineers, as a professional class, though based upon justice, is, in a sense, a selfish one, and, in urging it too strongly, we might expose ourselves to the charge of being actuated by a desire to gratify professional pride or vanity. Fortunately, the real motive for the evolution of the engineer in social and civic directions is one that is quite altruistic, for the benefits which will result from it for the engineering profession will be trifling in comparison with the benefits to the community, to the state, and to humanity in general. This may seem to be a broad statement, but it can be demonstrated.

We know that it is the engineer who, in the last hundred years, has effected the marvelous transformation in the material conditions of life and in the activity of communities which are startling to the historian, and which seem revolutionary to the superficial observer. The engineer has been too busy himself with the multifarious details of this gigantic task to note that what he has done has, in reality, reacted upon the whole structure of civilization to an extent so great that profound alterations, if not entire remodeling and reconstruction, are needed to restore balance and equilibrium. Now, in this task of industrial, social, economic, and political rearrangement and readjustment, there is work for all classes; and, considering the highly technical character of many of the problems involved, there is, especially, much work for which the training and experience of the engineer are important if not indispensable qualifications. It is here that we need the voice and authority of the citizen who is also an engineer; but his place is taken and his authority assumed by the lawyer, the politician, the agitator and the utopist, each having as little useful technical knowledge as the other, but each presuming, nevertheless, to be an expert and an authority on questions that are beyond his ken. Let us note here a significant fact. Public opinion holds so much in consideration and has so much respect for the older professional classes,—law, medicine and theology,—that it would not tolerate the suggestion that the tribunals of justice should be administered by others than jurists, that questions of sanitation or hygiene should be decided by others than medical men, or that moral questions should be settled by others than clergymen When, however, it comes to questions involving scientific and engineering knowledge, public opinion seems to be satisfied to let them be discussed and settled by anybody whatever, preferably by *others* than engineers.

In older times, men could qualify for handling the problems of the civilization of their day without reference to technical science, as knowledge of law and religion was the fundamental requirement. A very little science went a long way in an age when sophistry and credulity were at a premium. As a result of the rapid progress of civilization along scientific lines, the importance of law and religion now sinks into insignificance, in comparison with science and technical knowledge as qualifications for dealing with the problems presented for solution. It does not require much thought or imagination to see that, in a society which is becoming daily more and more dependent upon science and engineering for its welfare and well-being, aye, for its very existence, there is more and more room and need for men of technical training at the helm in public affairs.

Some thirty years ago, the then president of these United States stated that "we are confronted by a condition, not a theory." Today, we have a different state of affairs. We are confronted by both conditions and theories, more especially by a great number and variety of theories, many of them of questionable soundness. This conglomerate condition is owing to the fact that we have too many "quacks", and not enough "doctors", in economics.

A sage of bygone times uttered the aphorism that there is no royal road to learning. Now, the world would not be so much disturbed or inconvenienced, if it were only royalty that aspired to acquire learning without having to pay the price. Unfortunately, that disposition has become epidemic at the present time, and what is still worse, the appearance is often accepted for the reality, so far as knowledge is concerned, more especially knowledge of civics and economics.

The framers of the constitution of the United States, in making a general statement that "all men are born free and equal," without making it clear that they meant freedom and equality in a civic and legal sense, rather than in a social or intellectual sense, left room for much misunderstanding and confusion. The untutored mind finds encouragement here for the notion that one man's opinion is as good as another's. He does not distinguish between the *right* to express an opinion, which is a matter of *law*, and the *value* and *authority* of that opinion, which are matters of *knowledge*. He forgets that while the right may not be disputed, the authority may be both disputed and denied. This self-constituted authority is a source of great

mischief, and it is, perhaps, the indirect cause of much of our social unrest or political inconsistencies and our economic disturbances. We are forced to realize and to admit that it puts a premium on ignorance.

The same process of reasoning that makes a man think he is an authority on all political questions makes him a partisan of direct legislation in its most radical forms. Instead of matters being improved, they are made worse. The reason can readily be seen. The burdens thrown upon the individual increase in proportion with the responsibilities which he assumes. In presuming to deal with and pass upon all civic, economic and political questions directly, instead of delegating them to representatives, he assumes implicitly the responsibility for informing himself about every matter, and getting at least as intelligent a grasp and comprehension of it as the representative is presumed to have. But here is precisely where the trouble arises. Many of the questions which he has undertaken to answer for himself, in doing away with representatives and proxies, and in becoming his own authority and guide, are questions involving and requiring more or less thought and study and inquiry into facts. It is work of a kind for which the average citizen has not the time or the inclination, even if he had the aptitude and the training. How can enlightened thought and opinion and rational action be realized under such circumstances? It seems natural to expect that most of the untutored and indifferent minds in the community will either jump at conclusions or arrive at them in a very superficial way, very much as one may try to get the news by merely reading the heavy headlines in a newspaper. In such a case, it is very important that the headlines should be set up by men who are intelligent, well informed and honest.

It is a momentous question which is asked when we inquire whither the untutored citizens, who constitute always such a large part of the whole mass, will turn to read these headlines, in their search for information; and the answer is far from reassuring. Some may read them in the sermon of a popular divine who is trying to fill the pews by observations on civics, economics, and other technical subjects of which he knows precious little. Others may read them in the speeches and harangues of agitators and fanatics, and no doubt many others find them in the corner saloons in the vaporings of some would-be sage, who, after finding inspiration at the bar, tries to imitate the sapient "Mr. Dooley" in solving the world's problems.

The sum total, the net result, of all this dilettantism is a condition wherein the blind are leading the blind. All this confusion, and all the blundering which it entails, could be and may be avoided by putting men and things back into their proper places. In seeking for causes, we are brought face to face with important facts. First, the present disregard for knowledge and authority among the masses, and the transition from a state or condition where a few privileged professional classes or sects were the only ones who presumed and were permitted to think and pronounce on public questions, to a state where all classes and, in fact, all individuals, assume the right and authority to do so, are undoubtedly consequences of long-continued abuse of authority by those who presumed to be the oracles of the people, and made believe that they knew all about things which, in reality, they did not know. Second, it is mainly lack of *scientific* knowledge that has caused the old-time oracles to fall from grace in the popular estimation. The days when scientific facts could be over-ridden and overshadowed by rhetoric and oratory, are passed. An ounce of technical knowledge is worth a ton of imagination, when it comes to handling scientific facts. The public lost confidence in its oracles because it found out, in time, that it is more important for statements to be *true* than to be merely *plausible*. Third, the public is not to blame for not having given to men of scientific training an opportunity to enlighten and advise it in matters of scientific fact and knowledge. The blame lies with the men of the scientific class themselves, for having allowed the public, as a body politic, to remain in ignorance of their very existence, to say nothing of their qualifications. It is unfortunately too true that the civil and social status of the professional engineer are far from being well defined in the mind of the general public. Indeed, there are indications that the scientific education, training, and experience of the professional engineer are very little understood and appreciated in the community. It is not strange, therefore, that the professional engineer should, by many, be regarded as merely a higher grade of skilled mechanic or artisan. To remedy this condition, steps should be taken to inaugurate and carry on a campaign of education of the public, with the object of acquainting it with the engineering class. It is time that engineers should assert themselves as a class and let the public see that they satisfy very substantially the requirements of an intellectual class, and one of more than

average grade, as well as of high civic character; that, as such, they are qualified to render important service to the community and to the state, and are entitled to recognition.

I wish, at this point, to make it plain and emphatic that the kinds of service and of recognition that I have in mind are not of political, but more of civic, social and ethical nature and character. I would be sorry to see any body of scientific men become a political force and acquire ambition for political power. It would be a lamentable waste and perversion of mental energy of high quality and development. In the beginning of this portion of my address I spoke of the development of the higher and better sides of human nature, and of the evolution of character along the lines of highmindedness and refinement, as the path over which man can attain to the highest civic and social planes. It is my opinion that not only the engineering class is capable of this higher development, but that it can serve as a strong leaven to promote that development in the community. In a word, I believe that, just as engineering has helped materially to improve physical conditions, so the engineering class can help materially to improve civic, ethical, economic and even moral conditions, in modern life. The education, the training and the experience of the engineer fit him especially for such a mission. He has to deal less with fiction and more with facts than most men of other intellectual classes. He learns early to understand and appreciate the value and the utility of scientific method and precision in his habits of thought and expression as well as in his work. He also learns early to distinguish between the classes of subjects with which he is competent to deal, and on which he may presume to speak authoritatively, and those classes of subjects which are not within his sphere or his scope, and in reference to which it would be absurd or even impertinent for him to pose as an authority. He knows that specialties in intellectual work arise from the limitations of individual mental aptitude and energy, and he is willing to concede that the specialist is likely to have more and better knowledge of a given subject than the amateur. He *might presume* to express an opinion on subjects involving *scientific* or *technical facts;* he *would hesitate* to express one on subjects involving scientific *hypotheses* or *theories;* and he *would be quite reticent* on subjects involving *metaphysical* considerations or speculations. The subjects of the class first mentioned may be presumed to be wholly within

his sphere; those of the next class are likely to be only partly so; and those of the last class are, as a rule, entirely outside of his sphere. The man who has been taught and trained to exercise such discrimination and discretion is qualified for sane, sound, rational, logical thinking; he is apt to be more careful and accurate in his statements; he usually says what he means and means what he says; and his opinions are bound to carry weight and receive consideration. They make an interesting contrast with those of the man who undertakes to cover all subjects with equal "fluency". It is well known that, as a rule, engineers and scientific men are more conservative in their statements than most men of the other educated and intellectual classes. This is the result of a better appreciation of the limitations of all human knowledge and of the importance of precision in thought and expression; it is, in a word, the result of better intellectual perspective and mental balance. These qualities are very valuable in the citizen, in the member of a community, as they are known to be in the engineer entrusted with important tasks. They only need to be known to be appreciated. They should enable the engineer to command the respect and receive the consideration of the general public, for they are bound to place him on a high civic plane, and make him an exemplar for the rest of the community.

That is the position to which I would like to see the engineering class attain. The other educated intellectual classes have had their "inning,"—their opportunity. Ours is yet to come. Deserve success and you shall command it. We must deserve and we shall obtain the confidence of the community; and when we secure it we must retain it, by continuing to deserve it. The engineering class can scarcely expect to reach the goal at one bound. It must expect to attain the higher position to which it is entitled among the thinking and intellectual classes by successive stages. It should delay no longer, however, in making a start and in taking the first steps.

I have not by any means exhausted the subject. There is a great deal more to be said, but I shall be content if I have aroused your attention to the importance of not neglecting our evolution along social and civic lines, and beyond the purely technical and professional lines which we have hitherto looked upon too much as being our final goal and the highest realization of our ideals.

I will offer, by way of conclusion, some thoughts summing up the situat on, which, I hope, will receive your careful considera-

tion and will be borne in mind by you as having an important bearing upon the further evolution, in a civic and social sense, of the members of this Institute.

I. The Institute has made most satisfactory progress in the development of the activities and forces which conduce to its efficiency, which enhance its merits and enlarge its reputation as a forum for the discussion of questions and the study of problems in theoretical and applied electrical science. Its evolution in that sense and direction has been rapid and healthy; and it bids fair to continue to expand its sphere of usefulness.

II. The membership of the Institute, as a whole, has shown extraordinary devotion and loyalty to its interests, and a most edifying zeal in constant efforts to place it on a high plane among the engineering societies of the world.

III. The members of the Institute, as a class, have great respect for high professional ideals and ethics, and they have given enthusiastic and strong support to all movements and measures tending to their development in the Institute.

IV. The members of the Institute, in common with those in the other engineering societies in this country, have paid but little attention to the cultivation of professional ideals outside of the Institute.

V. As electrical men we have pre-empted and we hold a high position in that inner world which constitutes the engineering hierarchy. We have not attained the same high relative rank and position in the outer world, in civil and social life.

VI. In spite of the wonderful achievements which we have performed and the great contributions to the progress of civilization for which we deserve substantially the entire credit, we do not hold the place in the social scale that is commensurate with our professional attainments and our social qualifications.

VII. We have measured our weight and influence as a class by reference to what we think of each other, and by our mutual respect and consideration for each other, forgetting that our social position and status are determined wholly by what the outside world thinks of us, or the respect and consideration which it accords us, or which we demand and obtain from it.

VIII. The time has arrived when the members of the Institute should develop a class spirit through which a man in the engineering profession can attain to the place and high honor and consideration to which he is entitled among the other professional classes.

IX. We must show to the rest of the world that engineers are, by education, training, and experience, as well qualified as any professional class, to discuss, and deal with, public questions and problems, and that in the case of technical questions we are better qualified than are the other classes.

X. We not only fail in our duty to our professional class, but we also fall short of doing our full duty to the community, by remaining silent, in the social and civil background, and by hiding the important light which we are most able to shed on many public matters, by virtue of our scientific and technical training.

XI. We must dispel the popular notion that clergymen, lawyers, physicians, and literary people are still, as in bygone ages, the incarnation of civic wisdom and the epitome of social philosophy, or that they still constitute the only available source of intellectual "high potential" and the only dispensary of advanced thought and knowledge concerning the problems of civilization and human progress.

XII. The engineering class must take its place on a social plane parallel with that of the other professional classes, and must claim, in connection with technical matters within its province, the same consideration and deference to its opinions and decisions that are shown to the other classes under similar circumstances.

Presented at the 31st Annual Convention of the American Institute of Electrical Engineers, Detroit, Mich., June 23, 1914, under the auspices of the Committee on Use of Electricity in Marine Work.

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ELECTRIC HEATING AS APPLIED TO MARINE SERVICE

BY C. S. MC DOWELL AND D. M. MAHOOD

ABSTRACT OF PAPER

Electricity is being adopted to a great extent for space heating in marine work because of the simplicity and low cost of installation, saving in weight, freedom from leaks, noises and disagreeable odors as compared to steam heat, availability for heating of individual rooms, ability of placing heaters where most efficient, portability so that storerooms and other seldom-used spaces may be readily heated when desired, ease of regulation so that individual staterooms, etc., can be maintained at any desired temperature without affecting the whole system.

A comparison of convector and radiant heaters is given, the proper use of each type is shown, and the conclusion drawn that for space heating on shipboard with metal decks and bulkheads, the convector heater is most efficient.

Curves are given showing results obtained on tests to determine the best type of heater for shipboard, and desirable features of heater are indicated.

With low cost of electricity on shipboard, electric heating compares favorably in cost of maintenance with steam heating. It interferes very little with the lighting load, thus increasing the load factor, and seldom requires extra generator capacity.

THE SUBJECT of this paper was selected because it presented a means of placing before the Institute the advantages of electric heating, which have become more prominent in marine than in land service; and because marine service has very thoroughly taken up this subject, with the result that many installations have been made. Electric heating, properly applied, fits itself well to the conditions of marine engineering, where the high quality of service and its many desirable advantages overbalance what increased cost of electric power there may be.

Electric cooking, with its many advantages, included in which are the saving in time and food, improvement in quality of food, ease of installing and operation, safety and sanitation, is well known, and it seems unfortunate that the use of such appliances has been held back in this country as much as it has, and is not receiving the attention it has been getting abroad.

The gradual increase in the use of electrically heated industrial apparatus is going on; the safety, saving in time and improved

quality of work creating a popular demand in many classes of apparatus.

Electric air heating of spaces, upon which we will go into detail in this paper, is now rapidly coming into popular demand, its advantages, properly applied, making it a worthy competitor of other methods of air heating in marine engineering. The increased cost of operation over steam heat, although high in proportionate percentage, is not very great in actual dollars, in view of the low cost of generation of electric power aboard ships, and is further balanced by the convenience of locating the heat source where most efficient use of it can be made, the simplicity and low first cost of installation, especially where the air space to be heated is far from the boiler or engine room, the possibility of reliable automatic control of temperature, the low cost of repairs with little attention required, and the improved quality of service with freedom from leaks, noises, disagreeable odors and the other inherent objections to steam heating systems.

In some cases in the past, electric air heating systems have been failures, but usually these have been traced down as resulting either because the apparatus installed was the wrong design or insufficient for the conditions, the conditions such that an electric air heating system should never have been selected, or the particular electric heating system installed did not suit the conditions existing. In some places a small two- or three-lamp radiant heater was installed to heat a comparatively large space, the small radiator being selected probably because of high cost of power or because of the desire for appearances rather than for performance. It should be carefully considered before electric heating is installed whether the advantages of this system will overbalance the reduced cost of operation with steam, as unsatisfactory results in some past installations have proved hard handicaps to overcome, and have prevented installations that would have been very creditable. Care should be taken in selecting the design of heater and most appropriate method of installation, rather than placing appearances first, with a resultant sacrifice of efficiency, which appears to have been the practise in some past installations. As with electric cooking and industrial apparatus, electric air heating can compete with other systems only because of its adaptability, and this must be considered and made use of or the system will be found unsuccessful.

Heat is dissipated, as we know, by conduction, radiation and

convection. In considering electricity for space heating on shipboard we encounter, as a rule, metal bulkheads and decks which are good conductors of heat, and every effort should therefore be made to minimize conduction losses. The radiant and convector heaters, named from the manner in which the heat is furnished, have different conditions to meet.

The radiant heaters or electric radiators dissipate the heat principally by sending off radiant energy, raising the temperature of opaque bodies in its path, and as they respond instantly when turned on, have been found adaptable where a small amount of immediate warmth and intermittent use is required, such as in rooms not in general use, and where it is not desired that the temperature of the entire room be increased. Their efficiency for space heating on shipboard depends upon the material of the bulkheads and decks. As these are, as a rule, metal, which is a very good conductor of heat, a large part of the radiant energy is converted into heat upon striking the bulkheads and decks, is carried by conduction through the skin of the ship to the water and lost, or carried through the bulkheads and decks to the surrounding compartments and lost so far as the individual compartments are concerned. A feature observed in the radiant heater, worthy of mention, is the feeling of satisfaction when sitting in front of it (absent in a convector), caused by the cheerful glow present and, as has been stated by some authorities, the additional possibility of a physiological effect caused by the radiation of the higher frequency rays of infra-red, such as is experienced in sun baths.

Convectors heating the air in contact with resistance units, start convection currents which increase and maintain the temperature of the whole room. In space heating, where the surrounding walls are of metal, it has been seen that radiant heaters are inefficient in heating the air, and for this same reason in convectors the radiation losses should be kept down to a minimum. As the radiation increases as a function of the temperature, the temperature of the element should be kept low. Also it is better to heat a large volume of air a few degrees than a small volume of air a proportionately greater number of degrees. The former, instead of rising rapidly to the top of the room and there losing its heat through the metal deck above, will spread out more and warm by convection the air of the whole room.

To indicate the division of forms of heat dissipated by the

convector and radiant heaters the following was experimentally determined, using standard constructions:

	Radiant heater	Convector heater
Convected heat....	40 per cent	90 per cent
Radiated heat.....	55 per cent	5 per cent
Conducted heat....	5 per cent	5 per cent

The design of radiator appears to have settled on the glow-lamp type, although resistance wires operating at a red heat are coming into use. The location of the radiator is facing and within three or four feet from the person using it. In the standard designs of radiant heater, the glow lamp is the source of heat, and the

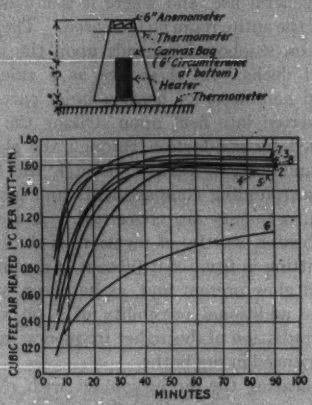

FIG. 1—AIR HEATED BY VERTICAL DRAFT.

commercial designs include two, three and four-lamp units, the lamps being either 250 or 500 watts each, as desired.

The design of convector heaters of the various manufacturers differs principally in the details of construction of the heating units. The formation of resistance units constructed of special resistance wire or ribbon, insulated and protected in various ways, and operating as close as practicable to a temperature best suited for the supply of convected heat, mounted in a manner to permit of efficient circulation of air, protected by a strong guard which does not restrict circulation and provided with a properly shaped deflector to give distribution of air desired, makes up this form

of heater. Practise has settled upon a long, low heater as preferable, which design, aided by a properly shaped deflector, permits of sending the heated air out from the floor, where better mixture and uniformity of temperature is obtained without the danger of concentration of high heat at the ceiling with a greatly reduced temperature lower down. A case has been cited of poorly installed heaters where the upper berths of staterooms have been surrounded by air at such a high temperature to make it uncomfortable, whereas a glass of water placed on the floor has been close to the freezing point.

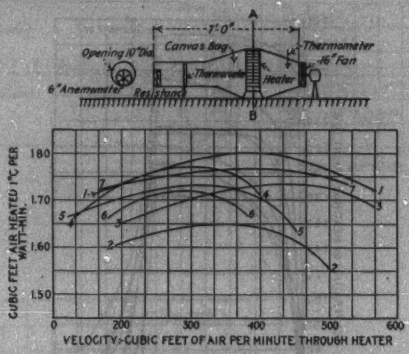

FIG. 2—AIR HEATED BY FORCED HORIZONTAL DRAFT.

No.	Input.	Cross-section A—B
1	3300 watts	169 sq. in.
2	2340 "	180 " "
3	3000 "	238 " "
4	1760 "	121 " "
5	2240 "	210 " "
6	1220 "	138 " "
7	3250 "	130 " "

The design of the heating element is influenced greatly by the desired standard of safety to be upheld, and this has brought out designs where the vibration and jar of marine service cannot cause disarrangement and possible arcing. Insulation of the supporting feet to prevent conduction of heat to the steel deck and bulkheads is looked after during installation and need not be considered in the design of the heater. The essential requirements of convector heaters are long life, maximum heat by convection available in a comparatively short time, a construction conveniently installed, safety, good appearance, and a flexible

design for different capacities desired in the various locations.

The operation of various designs of convector heaters is shown by the following curves obtained experimentally:

Fig. 1 shows the convected air by natural draft measured by anemometer and indicates the cubic feet of air heated one deg. cent. per watt-minute. This figure also contains a sketch showing the manner in which the convected air was measured.

Fig. 2 shows the air heated by forced horizontal draft, indicating in cubic feet of air heated one deg. cent. per watt-minute, and shows the variation with velocity of the operation obtained,

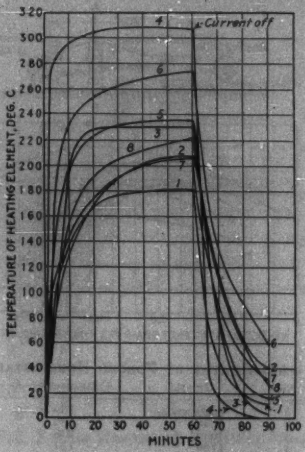

FIG. 3—CURRENT OFF AT END OF SIXTY MINUTES.

and is useful in considering such heaters for indirect heating, in which the heaters are placed in the ventilating ducts.

Fig. 3 shows the temperature rise of heating elements plotted against time for the respective heaters, and is useful in judging the performance of such heaters.

Fig. 4 shows the temperature distribution taken in a room 12 ft. by 21 ft. and 17 ft. high, with and without the use of deflectors of various shapes (see Fig. 11), and using one heater. Fig. 5 shows the temperature distribution in the same room as Fig. 4, only with the heater placed in the center of the room.

Fig. 6 shows the temperature distribution in a room 8 ft.

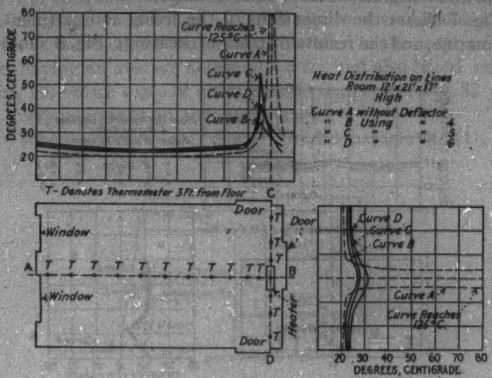
DEGREES, CENTIGRADE
Curve Reaches 125°C
Curve A
Curve C
Curve D
Curve B
Heat Distribution on Lines
Room 12'x21'x11' High
Curve A without Deflector
" B Using " 4
" C " " 5
" D " " 6
T- Denotes Thermometer 3 Ft. from Floor
Door
Window
Window
Heater
Door
A
B
C
D
Curve D
Curve C
Curve B
Curve A
Curve Reaches 125°C
20 30 40 50 60 70 80
DEGREES, CENTIGRADE

FIG 4

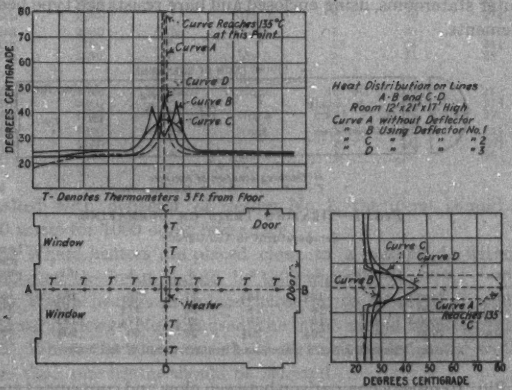
DEGREES CENTIGRADE
Curve Reaches 135°C at this Point
Curve A
Curve D
Curve B
Curve C
Heat Distribution on Lines
A-B and C-D
Room 12'x21'x17' High
Curve A without Deflector
" B Using Deflector No. 1
" C " " " 2
" D " " " 3
T- Denotes Thermometers 3 Ft. from Floor
Door
Window
Window
Heater
Door
A
B
C
D
Curve C
Curve D
Curve B
Curve A
Reaches 135°C
20 30 40 50 60 70 80
DEGREES CENTIGRADE

FIG. 5

by 15 ft. and 9 1/2 ft. high with heater placed at the side of the room and using deflectors of various shapes.

Fig. 7 shows the dimensions of the living compartment in a submarine, and the results of tests of heating; Fig. 8 shows the

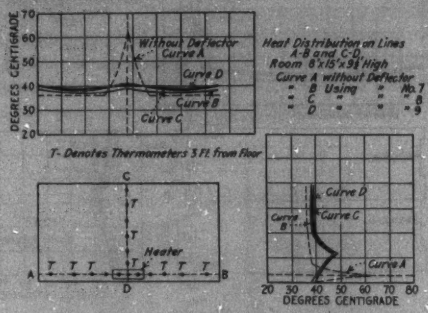

FIG. 6

dimensions of inner and outer staterooms and the results of tests of heating, and Fig. 9 shows comparative rise of inner and outer staterooms, using enclosed and bare resistance type heating elements.

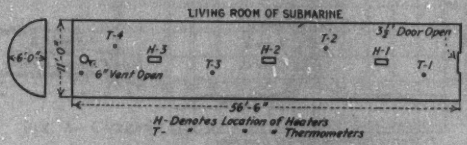

FIG. 7—HEATING TESTS ON SUBMARINE.

Temperatures in Centigrade

Hour	Total watts	Outside	1	2	3	4	Av.	Increase above outside
0	7600	8	16½	16½	17	16	16½	8½
2nd	7600	8	18	18	20	17½	18½	10½
3rd	7600	8	18	18	20	17½	18½	10½
6th	7900	8	20½	20½	22	20	20½	12½

NOTE: Deflector No. 3 placed on 2 heaters at end of 3rd hour.

Fig. 10 gives a comparison between glow and convector types of heater as regards convected heat given off, and Fig. 11 shows the types and arrangement of deflectors used in obtaining the data for the curves herewith.

From results of tests conducted during this investigation the following general results were obtained:

(1) For each 1000 cubic feet of space, 1500 watts input is required to maintain the temperature of air space of staterooms at 70 deg. fahr., based on the heater being installed in the center of the space, having an average height of 7.5 ft., and also based on replacing the entire space of air at outside temperature of 32 deg. fahr. every quarter of an hour.

(2) Where heaters are placed as in paragraph (1), but

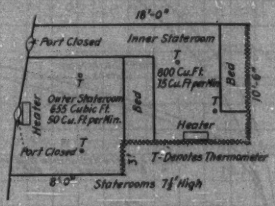

FIG. 8—HEATING TESTS IN STATEROOMS.

Hour	Watts	Position of heater	Type of deflector	Temperature in Centigrade: Outside	Passage	Room average
			Inner Stateroom			
2nd	2760	Center	None	10	20	22
3rd	2760	"	"	10	20	22½
5th	2360	"	No. 3	9	20	27½
3rd	2260	Side	None	8	20	24
4th	2260	"	"	8½	21	24½
7th	2530	"	No. 5	8	21	28
			Outer Stateroom			
2nd	2040	Center	None	10	20	21
3rd	2040	"	"	10	20	21½
5th	1740	"	No. 3	9½	20	27
3rd	1650	Side	None	8	20	25½
4th	1650	"	"	8½	21	25½
7th	1840	"	No. 5	8	21	29

installed with deflector of design No. 2, the input should be 1200 watts for 1000 cubic feet space.

(3) Where heaters are placed close to a bulkhead, without a deflector, the input should be 1300 watts.

(4) Where heaters are placed close up to a bulkhead, and a deflector of design No. 4 is used, the input should be 1100 watts.

(5) Where the space exceeds 20 ft. in either length or width, more than one heater should be selected.

It has been brought out by Dr. Langmuir that the heat loss by convection in small wires is nearly independent of the diameter,

and it has been found in electric convectors that with the units at the same temperature, the amount of convected heat given off per watt input, increases when the diameter of the unit is decreased. However, as the unit must be of substantial con-

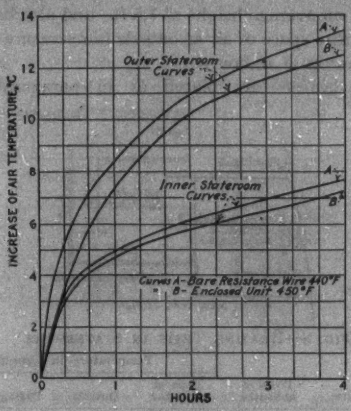

FIG. 9—COMPARATIVE TEMPERATURE RISE IN STATEROOMS

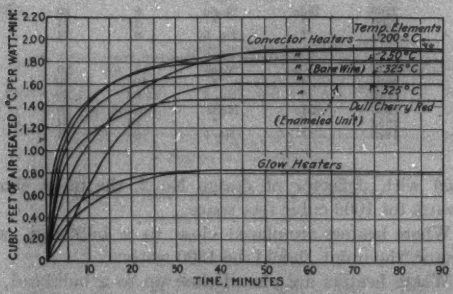

FIG. 10—AIR HEATED BY NATURAL VERTICAL DRAFT—COMPARISON BETWEEN GLOW AND CONVECTOR HEAT.

struction, the use of small diameter units is precluded, to some extent, by other considerations.

Convectors should, where possible, be fixed in or near the center of the room, but this is, as a rule, impracticable and it becomes

necessary to secure them near a bulkhead. The effect of their position on the heating of a room is shown in Figs. 4, 5 and 6. When mounted near a bulkhead, the heaters should be heat-insulated fron the bulkhead and the back of the deflector should also be heat-insulated so that the losses through the walls can be kept low.

The investigation, the results of which are shown in preceding paragraphs, was conducted in order that the advantages of the best features of design and installation might be made use of to bring up the efficiency of the installation and minimize the ob-

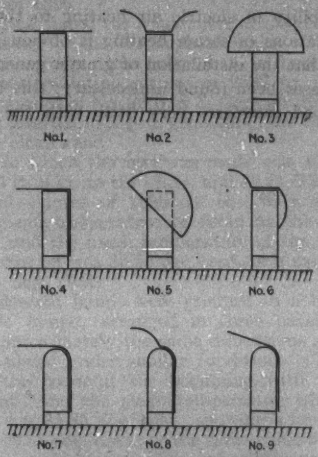

FIG. 11—DEFLECTORS USED.
Material No. 28 B. & S. gage sheet iron.

jection to the cost of electric air heating systems. The system of heating of spaces on shipboard which is now receiving most attention is a combination of steam and electric. Air for supply to spaces aboard ship is drawn in, by blowers from outside on the upper deck, through steam coils known as a thermo tank, and delivered to the spaces at about 50 deg. fahr. In each stateroom an electric convector heater is installed by which any additional increase in temperature is available to the occupant, and such temperature may be maintained by an automatic regulator thermostat installed in the convector circuit. This very conveniently re-

moves the difficulty existing with the steam installation with its common piping system—that of the desirability of different temperatures for occupants of adjoining staterooms—and reduces to an inappreciable amount the additional expense of electric over steam heating.

The cost of generation of electricity aboard ships having boilers already installed for propulsion is about one cent per kilowatt-hour and in some cases is less than this value. At such a low cost of generation, the great objections met with on land installations of electric air heating where the cost is as high as fifteen cents, do not prevail.

The adaptability of electric air heating to the extension of original installations of steam heating is obvious, and investigation shows that the installation of greater generator capacity has in most cases been found unnecessary; this being because the heating load interferes very little with the cooking and lighting loads.

DISCUSSION ON "ELECTRIC HEATING AS APPLIED TO MARINE SERVICE" (MCDOWELL AND MAHOOD), DETROIT, MICH., JUNE 23, 1914.

W. S. Hadaway, Jr.: The paper by Messrs. McDowell and Mahood is of value in showing that while different types of heaters develop the same amount of heat with the same input, their effective value may vary according to conditions of service.

The *Electrical Engineer*, New York, January 20, 1897, published tests on "Incandescent Lamps vs. Commercial Heaters." The authors were E. Y. Young and C. D. Warner, and the tests embodied a series of experiments at the University of Nebraska, in the spring of 1896.

The apparatus tested for a commercial electric heater was a 3½-h.p. car heater of the Wittingham make. The heater consisted of twelve wrought iron tubes, 1 in. in diameter, 6 ft. long, and had a total radiating surface of 2592 sq. in. Each tube carried three strands of No. 20 B. & S. German silver wire twisted together, and inserted in a ¼-in. glass tube, the whole being then filled in with clean sand.

The room in which the test was made was 10 ft. long, 7 ft. 9 in. wide, 16 ft. 8 in. to the plate, and 19 ft. 2 in. to the ridge, giving a total volume of 1396 cu. ft. With the commercial heater, the mean temperature of room at the beginning was 19 deg. cent. and the mean temperature of the room when the current was shut off was 35.55 deg. cent., or a mean temperature rise of 16.55 deg. cent.

The incandescent lamps were grouped in a bank of 75, 16-c.p., 110-volt lamps, arranged in three parallel rows. The heater had approximately the same dimensions as the car heater, and was tested under similar conditions. The mean temperature of the room at the beginning with the lamps was 19.3 deg. cent., and the mean temperature when the current was shut off was 35.85 deg. cent., showing a mean temperature difference of 16.55 deg. cent., or the same value as obtained with the Wittingham car heater. The only difference in the results is in the rate of temperature rise. It is shown graphically in the paper for purposes of better comparison.

From Fig. 9, in the McDowell and Mahood paper, it would appear that it was possible to heat an outer stateroom, with the same amount of energy, more rapidly than an inner stateroom. In view of the fact that the findings are modified by the peculiar shape of the room as shown in Fig. 8, it would seem desirable to state that the shape of the rooms has more to do with these results, than their location.

The only point to which we take exception is the fact that the authors are assuming a somewhat extreme position in reporting that the tests on the radiant heaters indicate a less effective structure than the convector type. While the curve in Fig. 10 seems to confirm this position, it would be desirable to carry

out the tests more carefully, and for longer periods of time, to confirm this conclusion.

The general conclusions as to the adaptability of electric heaters in marine service are encouraging. The modern ship is an industrial power installation of the most compact type, and the improvement in load factor by a mixed heating and cooking load would make an investigation of additional interest.

Alfred E. Waller: The curves shown in this paper, so far as rapidity of obtaining heat is concerned, appear to indicate a certain amount of advantage in favor of the open wire coil heater. It is my belief, however, that the advantages obtained by using heaters with entirely protected coils more than offset the slight advantage gained in the quick heating of the open coil type.

Enclosed or protected resistances can be made to reach their maximum temperature almost, if not quite, as quickly as the open type, and the extra time required to reach this maximum temperature is relatively unimportant if we compare it with the total time the heater is in use.

Suppose, for instance, that an open coil heater emits heat at the required rate twenty minutes after the switch is closed, and an enclosed heater takes forty minutes under the same conditions. This is an extreme case, and does not by any means represent the best performance to be obtained with the enclosed type heater. Under these circumstances, if the heaters are run for twelve hours, one takes 1/36 and the other 1/18th of the total elapsed time to reach full heat.

Disregarding this question of initial heating until it can be further investigated, I recommend the use of heaters with fully enclosed or protected resistors, for the following reasons:

Heaters are designed with two main objects in view—the first, that they shall give off heat, and the second, that they shall continue to operate for the maximum possible length of time with the minimum of repairs and replacements of units. It seems therefore very necessary that the resistance element should be protected in some manner, so that the moisture encountered in marine service shall not come in contact with the resistance.

A protecting layer of insulating and heat-conducting material, placed around the resistance wire or ribbon used in a heater, may be so arranged that it will not only exclude moisture, but will also protect the resistance material against chemical depreciation or mechanical injury of any kind. The support given the resistance element throughout its entire length is another advantage.

The possibility of short circuits, grounds, and dropping of molten metal which may occur as a result of burn-out in an open coil resistance will be readily appreciated. In a properly designed unit of the enclosed type, this danger is entirely eliminated.

One objection which has been urged against the enclosed type is that the weight is greater than that of an open type resistance.

This is not necessarily true, for the enclosed type resistance unit may be made considerably smaller than the open type, even if the total area of each heating unit is the same. This is because open coil units must be made of wire much heavier than is necessary in constructing an enclosed type unit, in order that the resistance may be mechanically strong enough to stand up in service.

I believe there is room for considerable investigation along one or two lines. One of these is whether it is not possible to use an enclosed type resistance run at a relatively high temperature, and to surround this by baffle plates or deflectors, which will cut off the radiant heat referred to by the authors, and at the same time permit a compact, mechanically strong and adequately protected unit to be used.

Another point which occurs to me, is the outside paint or covering on the heater. Dr. Carl Hering has published a number of discussions in the last few years on the general subject of surface resistance to thermal flows. These articles emphasize the influence which the outside surface of a body has upon the convection and radiation of heat. Related to the same subject is a paper presented by Dr. Irving Langmuir before the American Electrochemical Society. In this he discussed the effect of a polished silver surface.

Another interesting example is a foundry of which I have heard, in which the workmen whitewashed the outside of the furnaces, because they were then able to work near them in more comfort. The whitewash apparently had the effect of producing a high contact resistance between the furnace and the surrounding air, and the heat loss by radiation from the outside of the furnace was reduced.

The temperature of the outside of this furnace was found to be several degrees higher after the whitewash had been applied, this being the result of stopping part of the emission of heat by radiation.

It is an interesting paradox, if we consider two furnaces of exactly the same type and size, operating at the same internal temperature, one whitewashed and the other not whitewashed. In this case, the furnace with the hotter exterior would be operated with the greater efficiency—a condition which appears unreasonable until the attendant conditions are known.

Charles D. Knight: There are a few points I would like to draw attention to in connection with the paper. First, it is my opinion that the convector type of heater is much more efficient than the radiant. I also agree with the authors that it is better to heat a large volume of air to a few degrees than a small volume to a proportionately greater number of degrees. This is probably more important in the heating of houses than battleships, due to the fact that curtains, draperies and other material may come in contact with the heater.

The authors very clearly defined the amount of power required to heat a room of a certain area, and this brings up the

question of the very large gap that the power companies have to cover in reducing the price of power per kilowatt-hour. The authors have said that power can be generated in battleships for one cent per kw-hr., and I have no doubt but what the power companies can also do this, but when you consider the maintenance of the lines, and the expense of running them throughout the city over great distances, the cost becomes much greater.

When we figure out an ordinary size house, we will say with 20,000 cu. ft. of volume, we know that with hot air, hot water or steam it can be heated for $125 a year. Some rough figures, which I have made, will show that electricity at 5 cents per kw-hr. would cost very nearly $2,000 a year, and at 1 cent per kw-hr. about $400. It can readily be seen what the electrical engineer has to do in the matter of reducing cost of power to meet the competition which I have just mentioned.

D. B. Rushmore: I think it would be interesting, as this paper goes on record and is necessarily read by people outside of the Institute, if the authors will put in a little explanatory clause, as to how they calculate the cost of power on the battleship. That is a matter which is often misleading to people who are not familiar with the subject. I presume they leave out the original investment in the boilers and tanks, which would occur in a central power station. As an illustration, a man can raise coffee in Brazil, we will say, for five cents a pound, just as he can generate a kilowatt-hour, under certain conditions, we will say, for one cent, but the expense of getting the coffee into the hands of the consumer is what runs up the cost. It must be taken to the ship, brought to the country of consumption in the ship, then transferred to the wholesale houses, thence to the distributors, thence to the grocers, thence into the pantry at your home, which will probably cost about 35 cents per lb., and, therefore, you pay 40 cents per lb. for the coffee. That is the rough figure, but the figure on the cost of power is so disturbing to public utility companies just now, that unless an explanation is put in as to how this cost on the battleship is arrived at, the statement is apt to cause some misconception.

F. C. Caldwell: There is a very general idea that the radiant heater is too expensive in current consumption for common use in residences. The radiant projection of the heat directly upon the body to be warmed, however, makes it much more economical than is ordinarily supposed, and it is a great source of comfort as an auxiliary means of heating in a room where persons only occasionally gather. The absence of time lag in the effect obtained from a radiant heater adds greatly to its usefulness for such occasional duty.

We have found during the past year that the most appreciated electrical appliance in our household is an electrically heated blanket, or quilt, which consists of an ordinary bed-size quilt with a resistance wire woven all through it. This makes all the difference between comfort and pretty strenuous existence in outdoor sleeping, when the temperature is about zero. It

is something which should be used and appreciated much more than it is at the present time.

D. M. Mahood: I will take up the important points in the order in which they were presented, and comment on them as briefly as possible. Mr. Hadaway called attention to the variation in the curves in Fig. 9. We intended in that curve to show only the comparison between the bare resistor and the enclosed unit, and not a comparison of the heating of the inner and outer staterooms.

Mr. Waller commented on the comparison between the open and closed type of unit. Where it is possible to install an open rheostat without danger on a battleship, we can, of course, install a bare unit, but we would not think, for instance, of putting an open type of unit into a powder magazine or anything like that. It is the old story of adaptability—you must consider the conditions of the installation as well as the design of the material you are installing.

Mr. Knight and Mr. Rushmore both commented on the cost of power. The cost of ship-generated power, 1 cent per kw-hr., is the actual cost of generation. It does not take into consideration the cost of installation, depreciation, or the investment. In marine service, we have conditions very different from those prevailing in land work. We have the boilers, of necessity, for the purpose of propelling the ship, and the additional load for electric heating is small on the generating plant, and fits in very nicely with the other loads, the power and the lighting, and really, as a matter of fact, runs the boilers at a slightly better efficiency load.

Mr. Caldwell made reference to the radiant heater. The radiant heater is worked at a disadvantage in marine work, because we have the metal bulkheads which conduct off the heat received from the radiator. It is necessary, in order to use a radiant heater, to step right in front of it to get the effect of the heater. It is found that practically but little of the heat is sent off as convected heat, after it strikes the bulkhead—it is practically all conducted off. That brings us down to the convector type. The conditions on land are different. You have the wooden walls, which are poorer conductors, and for that reason the radiant heater has a greater field than it has in marine work.

H. A. Hornor: The battleship situation is one of metal bulkheads solely. In the merchant marine service, where you have the wooden bulkhead, and particularly out on the western coast, the conditions are more satisfactory. We recently built a ship to which we applied the radiant heaters. Practically every stateroom had a radiant heater of the three-unit type, and all public places had special fireplaces of the radiant heater type. It was a pretty effect, and the operation was very satisfactory. The conditions on the Pacific Coast are that the temperature changes are not violent, and the application of the heating apparatus to a passenger steamer was a good one.

Presented at the 31st Annual Convention of the American Institute of Electrical Engineers, Detroit, Mich., June 23, 1914, under the auspices of the Committee on Use of Electricity in Marine Work.

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THE ELECTRICALLY DRIVEN GYROSCOPE IN MARINE WORK

BY H. C. FORD

ABSTRACT OF PAPER

The gyroscope when continuously driven by electric power may be used for various purposes, many of its applications having especial value in marine work.

Small gyroscopes are used to establish base lines for the measurement or control of angular motion. The gyro-compass makes use of the earth's daily rotation and consequent changing direction of gravity to secure a directive force a hundredfold greater and more accurate than that of the magnetic compass.

A general description is given of the gyro-compass as adopted by the United States Navy for use on all the battleships and submarine vessels. Many electrical and mechanical devices have been developed to perform the various functions whereby an instrument of great precision has been secured.

Large gyroscopes are made which are capable of counteracting enormous wave forces and completely stabilizing any ship against rolling in the heaviest seas.

UNTIL a few years ago the gyroscope was little known or heard of except as a child's toy, although as far back as 1852 its action was investigated by the French scientist Foucault, who published the results of his experiments in which he laid down very clearly the laws of its action.

His first law states that any gyro or spinning body possessed of three degrees of freedom, *i.e.*, free to rotate about a spinning axis and two other axes all normal to each other, will tend to maintain its axis of spinning fixed in space and may therefore be used to show the rotation of the earth. He also demonstrated that when a gyro was given a forced motion of rotation about one of the axes, the gyro would powerfully resist such force while at the same time tending to place its axis of spin in line with or parallel to the axis of the impressed force. This motion which takes place about an axis at right angles to that of the impressed force is known as gyroscopic precession and always occurs in such a manner as to bring the direction of spinning the same as that of the impressed force, and by the shortest path. In

other words, if the spinning axis were horizontal and the axis of precession vertical, then the gyro, by virtue of the impressed force of the earth's rotation, would turn about in aximuth and place its axis of spin as far as possible in line with the earth's axis (*i.e.* upon the meridian) after the manner of a true compass. This strange resisting force with its unexpected motion of precession at a different angle and apparently unrelated to the impressed force, is in reality a simple and logical result of the inertia of the moving mass. Its explanation is well known and follows directly the application of Newton's laws.

It is not, however, the purpose of the writer to go into abstruse theoretical considerations. Suffice it to say that the law of precession explains fully the observed facts with regard to parallelism of the two axes, and is well illustrated in the accompanying figures, Nos. 1, 2 and 3, which show an ordinary gyroscopic top *A* mounted in a Cardan ring *B* by pivots *a*, the outer pivots *b* being supported upon a fork *C* rigidly mounted upon the base *D*. Suppose the wheel with all parts symmetrical, as in Fig. 1, is rotating clockwise, viewed from above, and we grasp the Cardan ring and depress it on axis *b* to position shown in Fig. 2. First it will be found that the Cardan ring is possessed of a quite remarkable amount of rigidity and opposes the forces tending to tilt it. However, as these forces are applied, and though the ring *B* is moved only slightly, yet the gyroscope is seen to immediately swing vigorously through a wide angle upon its axis *a* to the position also shown in Fig. 2. Upon lifting the Cardan ring the gyro will again be seen to swing vigorously in the opposite direction until arrested by the stop as shown in Fig. 3.

For nearly half a century after Foucault had demonstrated its action, the gyroscope was put to no practical use. The late American author and scientist Hopkins, whose writings were published for many years in the *Scientific American*, was the first to drive a gyroscope electrically. He was able to enlarge on Foucault's experiments and obtain much more persistent results with his continuously driven wheel.

The first serious application of the gyroscope in engineering work was by Obrey, an Austrian naval officer, who made use of the gyroscope to steer torpedoes. About 1903 Dr. Schlick, a German engineer, proposed the use of the gyroscope for stabilizing ships against rolling and built a number of experimental plants which were tried out with some little success. At about

the same time Lewis Brennan brought general public attention to the gyroscope by his announcement of a railroad car that would maintain its equilibrium on a single rail. A car of this type was exhibited in this country in 1910 and the subject of monorail traction was much discussed in the press at the time in connection with the possibilities for high speeds which were claimed for this invention.

Practically all of the serious applications of the gyroscope, and by far the most important of its uses at the present time, have developed in marine work. These are the steering of torpedoes, the use as a compass and the use for stabilizing and controlling the motions of ships, the last two of which will be discussed more fully.

Several minor applications have been made, such as (1) stabilizing of various instruments, telescopes, etc., against oscillations when mounted on a rolling ship; (2) stabilizing of a pendulum carrying a pen for recording the angles of roll and pitch of a ship; and, (3) stabilizing a horizontal mirror for use as an artificial horizon in taking observations at sea. Some very valuable results have been accomplished along these lines, but the limits of the present paper will not permit of more than a brief mention. Various attempts have also been made to stabilize a body with three degrees of freedom for use in the direct determination of latitude and longitude, but so far as is known, without practical success.

Fig. 4 shows a form of telescope used on board ship for obtaining bearings of distant objects, which has been stabilized by means of gyroscopes so that it is entirely unaffected by motions of the ship in any direction.

Fig. 5 shows one of several types of apparatus which have been constructed for recording the rolling and pitching motion of a ship upon a moving sheet. In the instrument here shown, records of the azimuth as well as various time markings are made simultaneously upon the same record sheet.

Errors are frequently introduced in navigation when measuring the altitude of a heavenly body above a false horizon caused by mist or by the mirage effect of the heated air on a tropical sea. Very frequent observations of the sun or heavenly bodies could be taken were it not that the horizon is obscured by low-lying banks of fog, or darkness.

Fig. 6 illustrates a gyroscopic artificial horizon which provides a means for eliminating these errors in observation and

makes it possible to measure accurately the altitude of any heavenly body that can be seen, whether or not the horizon is obscured.

The automobile torpedo, as is well known, depends upon a gyro steering gear for its directive power and would in fact be utterly ineffective for its purpose without such a device. The importance of the torpedo in warfare is of course recognized, so that the great value of this application of the gyro needs no further comment.

The gyro compass shown in Fig. 7 is now being installed upon all of the battleships and submarines of the United States Navy, where it is depended upon absolutely for use under battle conditions where the magnetic compass could not possibly be employed, due to the large masses of magnetic material constantly being moved about in proximity to the compass. As an instrument of navigation the gyro compass has also proved of great accuracy and value in enabling the ship to be held steadily upon its course irrespective of wind, sky or sea. The foreign navies are also rapidly adopting the gyro compass and it seems certain that its use on all of the larger steamships and ocean liners will be found in a few years when its great advantages have become more widely known.

The very high development of the gyro compass during the past few years has been largely due to the efforts of a pioneer in the electrical art, Mr. Elmer A. Sperry, whose long and interesting experience with gyroscopic phenomona and belief in their engineering possibilities led him to devote practically all of his time to its development.

It has been the privilege of the writer to be associated with Mr. Sperry for several years past in this work, during which time a plant has been organized and equipped for the design and manufacture of many forms of gyroscopic apparatus.

A number of workers abroad have also been laboring with great persistence and some degree of success to solve the many physical problems involved in translating the idea of Foucault into concrete terms of steel and bronze which will function under the extremely severe conditions on shipboard.

The nature of the problem is indicated when one realizes that the gyro compass is so sensitive that it responds instantly and with the highest degree of accuracy to the very slowly impressed angular motion in space about the earth's axis four thousand miles distant, while at the same time it remains indifferent

FIG. 1 [FORD]

Cardan-Mounted Gyro for Demonstrating Gyroscopic Precession.

FIG. 2 [FORD]

Precession Carrying the Upper End of Shaft to the Left by Tilting the Cardan Ring Downwardly.

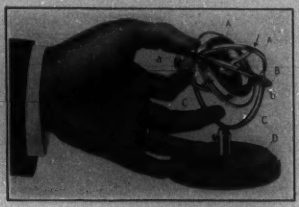

FIG. 3 [FORD]

Precession Carrying the Upper End of Shaft to the Right by Tilting the Cardan Ring Upwardly.

FIG. 4 [FORD]

Telescope Stabilized by Gyros.

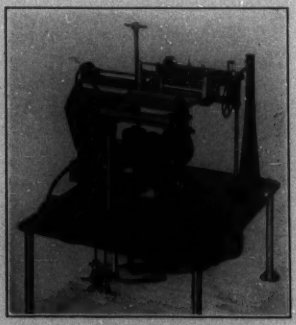

FIG. 5 [FORD]

Instrument for Recording the Rolling, Pitching and Yawing of Vessels.

FIG. 6 [FORD]
Gyroscopic Artificial Horizon.

FIG. 8 [FORD]
Model for Demonstrating the Action of the Gyro Compass.

FIG. 7 [FORD]
Master Compass with Covers Removed.

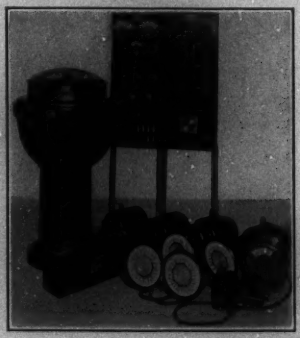

FIG. 10 [FORD]
Complete Equipment for a Gyro Compass Installation on a Battleship.

to the angular movements of the ship several hundred times greater in intensity.

In view of the extensive use of the gyro compass and the nature of the problems involved in its development, it may be of interest to look into the theory of its action somewhat briefly and then to note some of the many special construction details and various electrical devices employed in this highly organized instrument.

Fig. 8 shows a small device which may be used to demonstrate the action of precession in the gyro compass. In this device we have a small disk marked with the cardinal points to represent a compass card and mounted upon a ring swiveled to rotate on a vertical axis within a hand-supporting frame. The ring carries a wheel which spins upon a horizontal axis fixed in the ring parallel to the NS line of the compass card. If the device is held extended in the hand while the demonstrator turns slowly on his heel toward the left, we may consider his body as the axis of an imaginary earth and his head as the virtual north pole, since his rotation would always be easterly.

If the device is extended with the axis of the card perpendicular to the body at the waist line, the compass may be considered as located approximately at the equator. If held opposite the shoulder, with the axis of the compass card or handle making an angle of 45 deg. with the body, the compass would be represented in operation at latitude 45 deg. north.

Now when the wheel has been made to spin in a clockwise direction viewed from the south side of the card, if the device is carried about in the hand as above, the card will immediately orientate or turn on its axis to bring the north side toward the virtual north pole.

If the demonstrator should reverse his direction of rotation and turn toward the right, which would now represent east, we should have to consider that the north pole had been shifted to his feet, and if the little model is a true compass it should also reverse its direction and point to the new pole. This is what actually occurs, for the gyro compass not only holds to the meridian when placed thereon, but is actually possessed of a powerful north-seeking tendency many times greater than that of the magnetic needle.

The above demonstrates the elementary action of the gyro compass on an imaginary earth, the length of whose day is about twenty-four seconds. Under such conditions this little compass is ideal in its simplicity.

When, however, we are considering an instrument of precision, for actual use on a ship rolling, pitching and yawing in a heavy sea, or maneuvering at various speeds in every possible direction, the matter of picking out this demonstrator who will keep his body parallel to the earth's axis under such conditions and rescue a struggling directive force from the waves, is a somewhat larger contract.

As a matter of fact, many and serious are the mechanical and theoretical problems which had to be solved in producing a practical compass for navigation. For example, when mounted on a ship steaming rapidly north, say, the gyro axis does not point true north, but has a certain deflection, for the reason that the actual motion in space is no longer due easterly, but is about a resultant axis somewhat to the westward of the earth's axis. The amount of this deflection, which is a variable, depending upon the speed, course and latitude of the ship, has been exactly determined for all conditions.

In the Sperry compass a device is employed which corrects for the above factors and automatically introduces this correction into the compass readings, which are therefore always made accurately upon the meridian. Other special mechanical devices are employed for the following purposes, among others:

a. To provide a substantial mounting for the gyro element with the highest degree of sensitiveness.

b. To damp oscillations in azimuth.

c. To compensate various acceleration pressures.

d. To prevent errors caused by retardation of the wheel.

e. To set the compass quickly on the meridian even when the direction is unknown.

f. To prevent errors due to persistent oscillations in certain oblique planes.

g. To admit of determining the speed of the wheel by observation.

Space will not permit of a further study of the many theoretical problems involved nor of a detailed description of all the mechanical devices employed in this solution.

The general arrangement of parts constituting the Sperry gyro compass is shown in Fig. 9, which for greater clearness in illustrating the various functions has been simplified by the omission of electrical circuits and minor details.

The gyroscope wheel is mounted to rotate on a horizontal shaft A within the casing B, which is pivoted on the horizontal

axis C through its center of gravity and carried by the frame or vertical ring D.

The ring D is suspended by a torsionless strand E and guided by bearings F and F' to allow a free oscillation of limited amount about its vertical axis within the frame or "phantom" G, so called because of its characteristic action as a "shadow" in following up each motion of the ring D. The phantom G has a hollow stem H to which the strand E is attached at its upper end, and the stem forms a journal for rotation in azimuth with respect to the supporting base frame J.

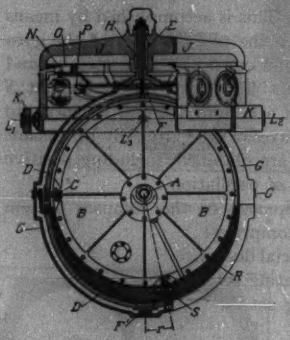

FIG. 9—METHOD OF MOUNTING THE DIRECTIVE ELEMENT

The frame J is mounted to swing in the binnacle by the usual Cardan suspension, consisting of the ring K and suitable bearings $L1$ $L2$, $L3$ and $L4$, the last not shown.

The frame J carries a "follow-up" motor M, driving a master gear N, forming a rigid part of the phantom G, whereby the latter is positively driven in azimuth to respond to any movement of ring D.

The ring D, which with the wheel casing is termed the "element," carries a pair of electrical contacts in the form of trolley wheels, which cooperate with stationary contacts mounted upon the phantom G for the purpose of controlling the follow-up motor M, the electrical connections not being shown in the figure.

The power-driven phantom G is thus automatically controlled so as to respond instantly to all movements of the sensitive element, and in fact to all relative movement in azimuth between the ship and the gyro.

This characteristic of the phantom enables it to be used for various important functions, namely, to carry the scale or card O and a cam P forming part of the automatic correcting device. The power drive is also utilized in operating the transmitter for the repeater instruments, and in overcoming friction of the slip rings needed to carry current to the gyro.

Since the phantom G, though at all times rigidly anchored to the binnacle, stands in practically constant relation to the sensitive element as regards motion about the vertical axis, but is nevertheless entirely separate therefrom, it serves as an anchorage for producing stresses to restrain and correct the movements of the sensitive element. This is accomplished by means of a yielding connection between the phantom G and the gyro case B, in the form of a pendulum or bail R, supported by and forming a part of the phantom. The point of attachment S to the gyro casing is located in a certain position eccentric to both the vertical and horizontal axes of the gyro. By this means several most important results are obtained, including positive orientation and the prevention of oscillation.

The complete electrical equipment of the compass system which will now be considered comprises:

1. A voltage regulator of special design.
2. A three-phase a-c. generating set.
3. A 20-volt d-c. generating set.
4. A d-c. emergency service.
5. An alarm system.
6. An automatic control and protective system.
7. Specially designed controlling switches.
8. The gyro motor.
9. A servo-motor or follow-up system.
10. A secondary transmitting and receiving system.

Fig. 10 illustrates the various parts of the Sperry gyro compass system for use on a battleship. The master compass and controlling apparatus are installed in a protected portion of the ship behind heavy armor. The repeater compasses are mounted at various points about the ship at the different steering stations. On a battleship, for instance, repeaters are supplied at the main steering platform, others on the bridge for taking bearings, one in the conning tower for steering during battle, one in the steering engine room at the stern of the ship, and in some cases one or more additional repeaters in ships provided with additional steering stations.

The compass is also used in connection with various other instruments for obtaining and recording various data.

A most important use of the gyro compass is on submarine boats which derive their power, when submerged, from storage batteries, the voltage of which varies at times from as high as 160 volts down to 100 volts at the end of a long run. An economical form of voltage regulator has been devised for such service.

FIG. 11 [FORD]

Rotor and Stator of the Gyro Motor.

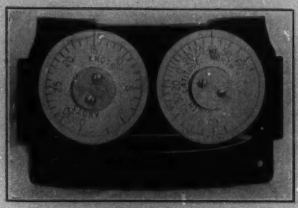

FIG. 13 [FORD]

Automatic Correction Dials, Setting 15 knots, 40 deg. North Latitude.

FIG. 12 [FORD]

Power-Driven Frame or "Phantom" arranged to Shield the Directive Element from External Disturbances.

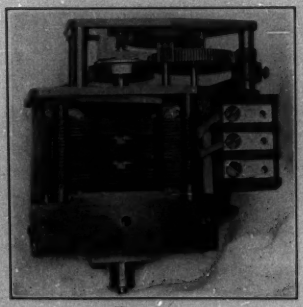

FIG. 14 [FORD]

Azimuth Motor for Driving the Phantom.

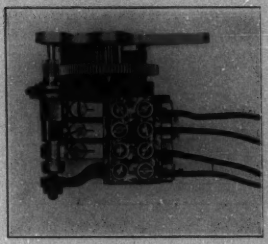

FIG. 15 [FORD]
Transmitter for Operating Secondary or Repeater Compasses.

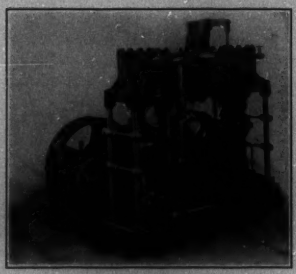

FIG. 18 [FORD]
The Precession Engine.

FIG. 17 [FORD]
One of the Two Large Gyros of the U. S. S. *Worden* while under Preliminary Tests at the Navy Yard, New York.

The problem of accelerating and driving the heavy balance wheel (the compass wheel weighs about 45 lb. or 20.4 kg.) at a velocity of about 8600 rev. per min. required the design of a special form of generator, three-phase current at 90 volts being used. The characteristics of the generator allow of the wheel being thrown directly upon the line and brought up to full speed automatically in about thirty minutes without attention on the part of the operator and without the use of excessive current. This machine, shown in the background of Fig. 10, has a capacity of three amperes per phase, but is ordinarily run under a load of 0.9 amperes.

The 20-volt d-c. dynamotor also shown in Fig. 10 is used in supplying energy to the servo-motor follow-up system and for operating the secondary or repeater compass system. No special features of design were necessary other than to meet the usual requirements on shipboard as to commutation, rating, accessibility, etc. In battleship equipments, both of the above generating units are ordinarily supplied in duplicate.

An emergency direct-current service is provided by the employment of a 20-volt storage battery which is kept floating upon the line at all times. This provides energy for operating the follow-up system of the compass whenever the ship's service has failed. During such times the gyro wheel, on account of its great inertia and ease of operation in vacuum, will remain spinning and will give ample directive power for an hour or more after the power has been shut off, so that the compass is rendered fully effective under all such conditions. This constitutes a unique and extremely valuable feature of the Sperry compass.

An independent six-volt battery and alarm bell are employed to notify the attendant promptly of any interruption of current or failure in operation of various parts of the system which would be likely to cause errors in the compass readings, so that the same may be corrected without delay. A trip relay is provided which keeps the bell ringing until the attendant has corrected the difficulty and reset the trip.

A reverse current relay is provided for disconnecting the direct-current dynamotor from the storage battery and line upon failure, or any material reduction in voltage of the generator or ship's supply line, and for connecting the generator in again when voltage has been restored to normal. This of course prevents the rapid discharge of the storage battery in driving the generator.

Especially designed switches and controlling apparatus are provided, which include a small and compact switch for throwing both the voltmeter and ammeter at once upon any one of a number of different circuits or phases. These switches are of the rotary or controller type and are enclosed in gas-tight cases to prevent danger of explosions when used in submarines.

The gyro motor is of the three-phase induction type, the squirrel-cage secondary forming a rigid part of the inner rim of the revolving wheel shown in Fig. 11.

On account of the high speed of the rotation, wheels have to be given a very careful running balance, which is accomplished by the use of various size studs threaded into holes at the periphery of the wheel on each side.

The stator also shown in Fig. 11 is mounted on one side of the main vacuum casing containing the wheel. A spiral line is painted on the wheel which, when observed through a window in the casing by means of a stroboscope, enables one quickly to determine the speed of rotation.

The servo-motor or follow-up system forms an important part of the gyro compass and performs three functions, of which the first is to shield the gyro from all external forces and friction. This is accomplished by the method of carrying the supporting filament, and all guiding bearings having to do with the sensitive element, within an outer frame known as the phantom (Fig. 12), which completely shields the element from all disturbing external forces.

The suspended mass of the sensitive element, which, including the wheel casing and the vertical supporting ring, weighs about seventy-five pounds, is by the above means rendered actively sensitive to a force couple of 1/4500 in-lb., which represents a force of less than one four-millionth part of its own weight acting at a radius of one foot. This degree of sensitiveness is actually measurable in the operation of the compass, which is thought to be somewhat remarkable in this respect.

A second function of the servo-motor, which in the gyro compass is known as the "azimuth motor," is to operate the transmitter for sending out indications to any number of repeater compasses located at distant parts of the ship. The main azimuth scale of the compass is also carried on the power-driven member.

The third function of the azimuth motor is to operate the

correction device before mentioned, which by means of cams solves a trigonometric equation involving the factors of speed, latitude and heading of the ship, and automatically introduces the proper correction into the compass readings, which are therefore maintained accurately upon the meridian. Fig. 13 shows the front of the correction device and dials which are set at the proper speed and latitude.

The azimuth motor with its reduction gearing is shown in Fig. 14, and is provided with ball bearings throughout. An inertia brake consisting of a balance wheel mounted and driven by friction on the armature shaft serves to damp the oscillations or hunting of the azimuth motor, while offering no resistance to continuous motion.

The secondary transmission system comprises a contact-making transmitter and six-pole step-by-step motor connected by three circuits having a common return wire. The transmitter (Fig. 15) is provided with three pairs of tungsten make-and-break contacts which are operated by cams. The construction of the repeater system is such that the motor may be driven at speeds as high as 1000 rev. per min., or 100 cycles per second, without getting out of step.

The repeater motor is geared to give six steps for each indicated degree in azimuth and the repeater compass instantly follows all changes of the master compass for every movement of the ship. The repeaters are provided with compass cards made of translucent material to permit of illumination from within.

A manually operated transmitter, or synchronizer, is used for setting the distant repeaters into agreement with the master compass in connection with a magnetic stop for each motor by means of which the repeaters are first collected upon a common reading and then brought at once to read with the master, which is then thrown into circuit.

The exceptionally fine results obtained with the gyro compass here described have fully justified the long and painstaking efforts that have been expended in its design and in the practical solution of the many problems met at various stages of its development and in actual use at sea.

When subjected to the most drastic tests, far greater in severity than any actual conditions found on shipboard, the compass continues to hold to the meridian within a fraction of a degree. In fact, every compass before being accepted by our Government has to pass through a series of such tests lasting several weeks,

during which time the maximum error must not exceed ½ deg. in azimuth when swung continuously for six days at a time under conditions of rolling, pitching and yawing of an artificial ship.

It should of course be understood that under similar conditions on board a battleship or submarine the magnetic compass would be almost if not entirely useless. Even under the best of conditions, navigation of a steel ship by magnetic compass entails a large amount of extra work with considerable liability of error in applying variation and deviation corrections of various amounts, plus or minus. With the gyro compass described, all readings are made exactly upon the meridian and the navigator is always sailing on true courses. The quick and accurate indications of the compass for the slightest deviation or yawing of the ship have enabled much straighter courses to be steered, with a resulting saving in fuel and increased speed. For intricate maneuvering in battle practise, the ship may be controlled perfectly from various protected steering stations and the master compass is completely shielded from the fire of the enemy and from the shock of gun fire.

In submarines the gyro compass enables an accurate course to be laid when running submerged, so that after obtaining the bearing of the target from a great distance the submarine may approach, submerged, to within a short distance and fire its torpedoes accurately.

From an instrument having a degree of sensitiveness to force couples measured by one four-millionth part of its own weight it is rather a long jump to consider another type of gyro possessed of many tons of stored energy which may be harnessed and made to work not only to hold a mammoth ship against rolling in high seas but actually to roll the ship for the purpose of sliding off a sand bar or breaking through an ice floe.

Gyros of this type have already been built, tested and thoroughly investigated and a gyro of thirty tons weight capable of exerting a force couple of over four million pound-feet is now under construction for stabilizing the S. S. *Ashtabula*, used as a car ferry on Lake Erie.

In two papers read before the Institute of Naval Architects and Marine Engineers in November 1912 and December 1913, Mr. Sperry has treated very ably and comprehensively the subject of stabilizing ships and has made some striking comparisons which show his valuable contribution to the art in the

"active" type of gyro. In the last paper referred to are shown characteristic rolling and damping curves for ships equipped with active gyros, when subjected to various wave impulses and frequencies. These curves, some of which are here reproduced in Fig. 16, were obtained from a model ship pendulum, the dimensions of which were adjusted to correspond to a 19,000-ton ship at the linear ratio of 1:30.

The stabilization is practically complete, as indicated by the curves in Fig. 16. Early in this work, observations were made indicating that the stabilization was complete even when the wave increments received from the sea were greater than the theoretical power of the gyros mounted in the ship.

The work with the stabilizer has shown that it is perfectly easy to stabilize against all wave increments received by the ship from the sea which are equal to or less than the stabilizing capacity of the gyro equipment. Stabilization is so complete under these conditions that interest in this part of the performance has been transferred to investigations of the region where the wave increments are actually in excess of the stabilizing capacity.

The curves in Fig. 16 are among the results obtained in this connection and it will be seen by carefully scrutinizing the cards that none of the curves are taken where the wave increments are not larger than the roll-quenching increment, and even under these conditions the stabilizing is practically complete for practically all the wave periods.

Practical data of great value were obtained from the construction of an active gyro plant which was tested out repeatedly on the U. S. S. *Worden* during the summer of 1912. This plant was the largest gyro installation ever built and consisted of two gyros weighing about three tons each which were operated actively by use of a precession engine.

The gyros were automatically controlled so that they responded instantly to all wave increments encountered, whether in harmony with the period of the ship or not.

Fig. 17 shows one of the *Worden's* gyros bolted on a heavy base plate while under test at the Brooklyn Navy Yard. The base was loaded with pig iron, which, with the load of the gyro and precession engine, brought the total weight up to over thirty tons. The gyro very effectively demonstrated its power by actually lifting this heavy load, tilting the whole base plate up on edge and rocking it back and forth as the gyro was precessed.

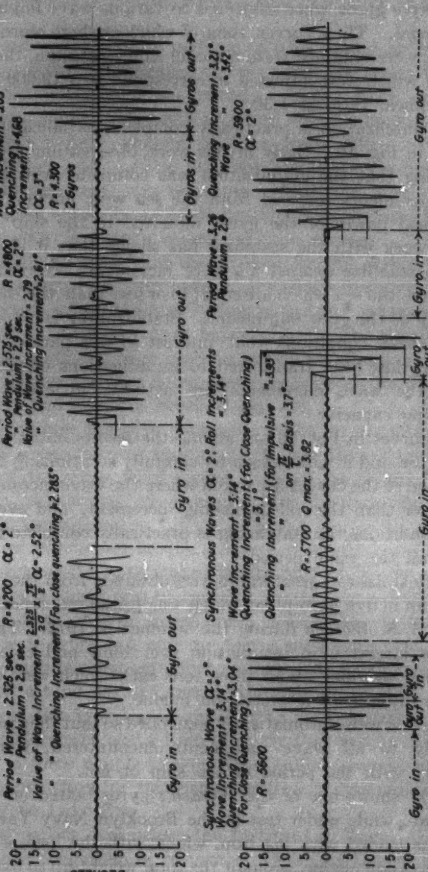

FIG. 16—CURVES SHOWING THE PERFORMANCE OF THE "ACTIVE" TYPE OF GYROSCOPE IN STABILIZING A PENDULUM SHIP MODEL AGAINST WAVE FORCES GREATER THAN THE THEORETICAL POWER OF THE GYRO

FIG. 19 [FORD]

The U.S.S. *Worden* at Dock.

Fig. 18 shows the precession engine, and Fig. 19 shows the gyro equipment mounted aboard the *Worden* ready for the sea trials.

The results prove conclusively that the active type of gyroscope as applied to the control of a ship's rolling motion is of vastly greater efficiency and economy than any other form of stabilizer yet proposed. The efficiency is demonstrated by the action of carefully calculated scale models and is completely verified by the long-continued performance at sea of the gyro plant on the *Worden*. The economy is evident from a comparison of the space and weight required in an installation of the active gyro relative to that required by the most effective form of water damping tanks or other stabilizing means.

Careful calculations show that an active gyro plant for stabilizing the S. S. *Ashtabula* will require less than one-tenth the space and weight which would be necessary for equivalent stabilizing with the best-designed water pendulum.

The results further show that it is now possible completely to stabilize any ship against rolling by means of an active gyroscope, requiring a very small percentage of the weight and space available in the ship. This work has opened up a wide field of usefulness in the application of the gyroscope.

DISCUSSION ON "THE ELECTRICALLY DRIVEN GYROSCOPE IN MARINE WORK" (FORD), DETROIT, MICH., JUNE 23, 1914.

Alfred E. Waller: There are two points I would like to ask Mr. Ford to explain further. One of them is, just what position the gyro occupies in the ship; for instance, just what is done to it to produce this rolling which has been shown to be so effective in breaking ice and getting a ship through a channel which would otherwise be obstructed?

The other thing I would like to have explained more in detail is this: I understand that the directive force of the gyro is a certain component of the angular motion of the earth, and at the poles this would be zero, so this should render the gyro ineffective at the poles. I would like to know to what extent the gyro is affected by extreme north or south latitudes.

H. C. Ford: The method of rolling the ship simply consists in forcing the precession or oscillation of the gyro about its vertical axis. When the ship rolls, the gyro tends to precess, and if this precession is allowed to occur, resisting forces will be set up proportional to the velocity of precession, which will partially stabilize the ship. To stabilize the ship completely it is necessary so to control the precession in time and amount that the varying wave forces are each counteracted by an equivalent gyroscopic moment. By forcing the precession, energy may thus be transferred through the gyro and the ship made to roll.

The gyro may be located in any convenient space that is available where the necessary bracing can be secured to the frame of the ship. Although the forces are large they are not excessive, being approximately of the same order of magnitude as the wave forces counteracted. It has been found that when stabilized, the ship is subjected to less strain than when allowed to roll freely. This is partly due to the fact that the waves are neither uniform nor synchronous with the roll of the ship. The freely rolling ship rides some waves easily, but frequently gets out of step and crashes into a wave with much greater shock than is the case with the stabilized ship, where the effect of the variable waves is reduced to a moderate average.

The size of gyroscope required to stabilize any ship depends entirely upon the proportions of the ship, which vary greatly in ships of a given tonnage. The gyro designed for the steamship *Ashtabula* is much larger than would be required for other ships of the same displacement, which would ordinarily have a smaller metacentric height. It may seem strange that the flatter, the more stable, a ship is, the more it will roll in a heavy sea, while a ship proportioned more like a cigar, with a low metacenter, will not roll, although it might capsize. The latter could be effectively stabilized with a very small gyro. The weight of the gyro installation required for any particular case cannot be given without quite extensive calculations.

Presented at the 31st Annual Convention of the American Institute of Electrical Engineers, Detroit, Mich., June 23, 1914, under the auspices of the Industrial Power Committee.

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DIRECT-CURRENT MOTORS FOR COAL AND ORE BRIDGES

BY R. H. MCLAIN

ABSTRACT OF PAPER

This paper gives a brief description of the mechanical arrangement of a coal bridge. The bridge consists essentially of a trolley car with hoisting mechanism for a self-filling bucket. A series-wound motor is recommended for driving the trolley car; and the proper method of gearing the motor for the most economical results is discussed. A series-wound motor is recommended for a low-speed hoist and a shunt-wound motor for a high-speed hoist. The relative merits of the two methods of winding the motor are considered.

A MAN trolley type coal or ore bridge consists essentially of a trolley car on an elevated railway carrying a self-filling bucket, with machinery for hoisting, lowering, opening and closing the bucket. The name of this type of bridge comes from the fact that the operator rides in the car. The bucket is suspended on two ropes, a "closing line" and a "holding line." If the holding line is stationary, the bucket will close when the closing line is taken in and will open when the closing line is let out. The elevated track or bridge spans a storage pile and usually extends out over a slip of water to cover a boat and often extends over railroad tracks on the other end. The bridge is supported on rails and can move along the storage pile.

Either one motor or two motors, in parallel, are used for propelling the trolley car. Generally two motors are used—one at one end and one at the other end of the car—so as to get uniform weight distribution and maximum tractive effort from the car wheels. Two hoist drums are used, one for the closing line and one for the holding line. The closing line drum is geared directly to a motor, while the holding line drum may be either driven from the closing drum through a clutch or geared to a separate motor.

Sometimes it is deemed advisable to use two motors geared together, instead of one, so as to get mechanical advantages in the trolley, such as even distribution of weight, and so on. For pur-

poses of this paper we will consider that one motor is used for propelling and that one motor does all of the hoisting. Where two motors are geared together and used as one, the characteristics are the same as if one motor were used, except that special precautions are taken in the design of the controllers to make the motors divide their loads properly.

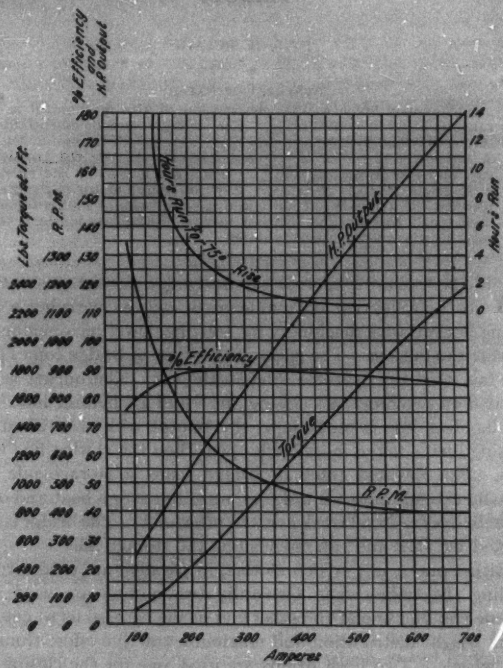


FIG. 1—SPEED-TORQUE-CURRENT CURVES OF A 100-H. P. SERIES-WOUND MOTOR

The problem for the propelling service is to move the car back and forth over the storage pile, making trips of various lengths, as quickly as possible. The distances vary from 50 to 600 ft. (15 to 180 m.), and the car speeds may reach a maximum of 1500 ft. (460 m.) per minute. A series-wound motor is well adapted for this service because it exerts about 50 per cent greater torque

per ampere on starting than on running. This feature makes a considerable saving in power consumption and power peak, as well as in the size of the motor, because most of the work of this motor is the starting and stopping of the trolley. The usual acceleration for the trolley is 1.5 to 2.5 ft. (46 to 76 cm.) per second per second. The speed for which the trolley is geared to run after all accelerating is completed—the "free running speed"—should be determined from the distance to be traveled and the time allowed for making the trip. For short trips the free running speed should be low and the accelerating rate high; while for long trips the free running speed should be higher and the accelerating rate lower. On a given coal bridge the average

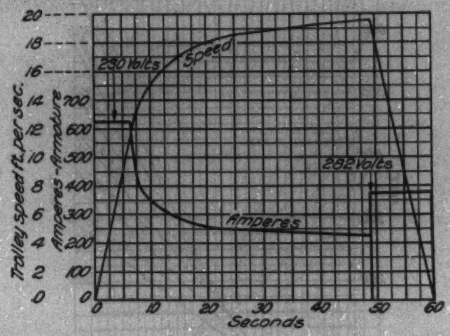


FIG. 2—SPEED-TIME AND CURRENT-TIME CURVES OF A 45-TON MAN TROLLEY, GEARED TO A 100-H. P. SERIES-WOUND MOTOR

Maximum speed of motor, 655 rev. per min.; maximum speed of trolley, 19.75 ft. per sec.

length of trip should determine the values to be used. In order to study the problem the writer has made up a number of curves showing the distance traveled in given times for various free running speeds and various rates of accelerating. These curves were made by plotting speed-time curves and integrating them to find the distance traveled.

Fig. 1 shows the speed-torque current curve of a series-wound motor. If this motor is geared to a trolley whose weight is 45 tons,* gear loss 10 per cent, rolling friction 35 lb. (16 kg.) per ton, free running speed 19.75 ft. (6.02 m.) per second, acceleration and retardation 1.8 ft. (55 cm.) per second per second, the speed-time curve will be as shown in Fig. 2. The area of this curve

*1 short ton = 0.90718 metric ton.

represents the distance traveled by the trolley in 60 sec. Figs. 3 and 4 show the net results of a number of curves like Fig. 2. Fig. 3 shows feet traveled plotted against seconds for free running speeds between 7.5 ft. (2.3 m.) per sec. and 25 ft. (7.6 m.) per sec., acceleration and retardation being taken as 1.5 ft. (46 cm.) per sec. per sec. Fig. 4 is like Fig. 3, except that 2 ft. (61 cm.) per sec. per sec. is used.

It is interesting to note on Fig. 3 that if only 75 ft. (23 m.) is to

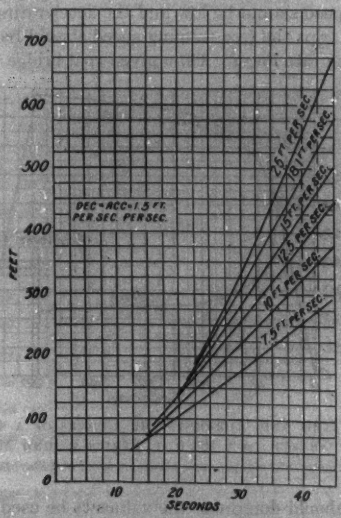


FIG. 3—DISTANCE-TIME CURVES FOR A 45-TON MAN TROLLEY GEARED TO A SERIES-WOUND MOTOR FOR "FREE RUNNING SPEEDS" VARYING FROM 7.5 TO 25 FT. PER SEC.

Acceleration equal to retardation equal to 1.5 ft. per sec. per sec.

be traveled it will take 14.5 sec. no matter whether the free running speed is more than 10 ft. (3.05 m.) per sec. or not. Consequently for 75-ft. (23-m.) trips there is no need of gearing for more than 10 ft. (3.05 m.) per sec. Likewise for a 150-ft. (46-m.) trip there is no need of gearing for more than 15 ft. (4.6 m.) per sec. It is easily understood that where low trolley speeds are used a given drawbar pull for accelerating can be obtained with the expenditure of less power than when high speeds are used.

It is also interesting to note that if 225 ft. (68.5 m.) must be traveled in 25 sec. and an acceleration of 1.5 ft. (46 cm.) per sec. per sec. (Fig. 3) is used, the free running speed must be 18 ft. (5.5 m.) per sec.; while if 2 ft. (61 cm.) per sec. per sec. (Fig. 4) is used, the free running speed need be only 13 ft. (3.9 m.) per sec. For distances less than 225 ft. (68.5 m.) the first method of gearing would require more time per trip and for distances greater than 225 ft. less time.

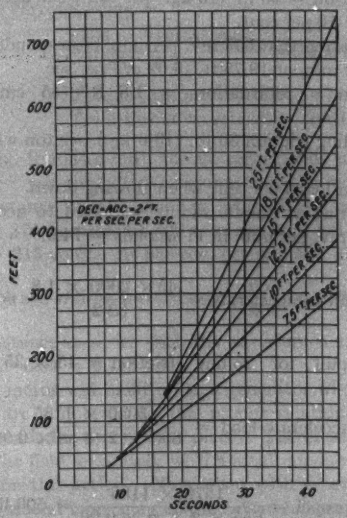


FIG. 4—DISTANCE-TIME CURVES FOR A 45-TON MAN TROLLEY GEARED TO A SERIES-WOUND MOTOR FOR "FREE RUNNING SPEEDS" VARYING FROM 7.5 TO 25 FT. PER SEC.

Acceleration equal to retardation equal to 2 ft. per sec. per sec.

For the control of a rack motor, simple rheostatic control of the automatic magnetic type should be used. On account of the large amount of kinetic energy to be dissipated when stopping the trolley it is advantageous to use the motor as a generator for stopping and thus save the maintenance of mechanical brakes. To obtain this braking, the armature, series field and a rheostat should be connected in such relation that the field will build up and the armature generate as shown in Fig. 5. The value of resis-

tance should be such that at the maximum speed of the motor sufficient current and voltage will be generated to give the desired rate of braking. As the generator speed decreases, the resistance should be decreased so as to maintain a uniform current and consequently uniform braking torque.

To determine the conditions of motor load let us take the case of the motor in Fig. 1 geared to the load described in Fig. 2.

Weight of load = 45 tons.

Rolling friction = 35 lb. (16 kg.) per ton when accelerating.

Gear loss = 10 per cent.

Motor so geared that 655 rev. per min. corresponds to 1185 ft. (361.2 m.) per min. or 19.75 ft. (6.02 m.) per sec.

Acceleration = retardation = 1.8 ft. (55 cm.) per sec. per sec.

Assume rolling friction 30 lb. (13.6 kg.) per ton when slowing down.

Assume gear loss 5 per cent when slowing down.

Pounds torque at one-ft. radius* required to accelerate the motor to 655 rev. per min. in 11 seconds = 74.5.

Then

$$\text{Drawbar pull to accelerate} = \frac{45 \times 2000 \times 1.8}{32.2} = 5040 \text{ lb.}$$

(2286 kg.).

Drawbar pull for rolling friction = 45 × 35 = 1570 lb. (712 kg.).

$$\text{Torque to accelerate load} = \frac{5040 \times 1185}{655 \times 2 \times \pi \times 0.90} = 1610$$

lb-ft.

$$\text{Torque to propel} = \frac{1570 \times 1185}{655 \times 2 \times \pi \times 0.90} = 500 \text{ lb-ft.}$$

Torque to accelerate armature = 74.5 lb-ft.

Total torque required while accelerating = 2184.5 lb-ft.

In Fig. 1, 2184.5 lb-ft. torque corresponds to 630 amperes. After all starting resistance is short-circuited and the motor is connected to 230-volt supply its speed will be (from Fig. 1) 405 rev. per min., which corresponds to 12.2 ft. (3.7 m.) per sec. Time required to attain this speed will be (12.2 ÷ 1.8 =) 6.8 sec. After this speed is attained the acceleration will be gradually reduced until uniform speed is attained. In Fig. 2 is plotted the current which corresponds to the speed and accelera-

*1 lb-ft. = 0.1383 kg-m.

ting rate of the car. After 19.75 ft. (6.02 m.) per sec. is attained, (19.75 ÷ 1.8 =) 11 sec. will be required to stop.

Drawbar pull to retard =

$$\frac{45 \times 2000 \times 1.8}{32.2} = 5040 \text{ lb. } (2286 \text{ kg.}).$$

Drawbar pull for rolling friction = 45×30 = 1350 lb. (612 kg.)
Net required drawbar pull = 3690 lb. (1674 kg.)

Net torque corresponding =

$$\frac{3690 \times 1185 \times 0.95}{655 \times 2 \times \pi} = 1010 \text{ lb-ft.}$$

Torque to retard motor = 74.5 lb-ft.
Total torque to retard = 1084.5 lb-ft.

From Fig. 1, 1084.5 lb-ft. torque corresponds to 375 amperes and 500 rev. per min. If we assume that the motor has an internal resistance of 0.04 ohm its internal voltage with an excitation of 375 amperes at 500 rev. per min. will be 230 – (375 × 0.04) = 215 volts. At 655 rev. per min and 375 amperes the internal voltage will be approximately $\frac{655}{500} \times 215 = 282$ volts.

The resistance in series with the armature must therefore be 282 ÷ 375 − 0.04 = 0.715 ohm.

A series motor will build up as a generator when its field and armature are connected in the proper relation, but it takes several seconds for this to take place. Therefore it is advisable to excite the field separately with a small amount of current so as to hasten this action. Now, even with separate excitation, about one second more may elapse before full magnetic strength is attained. During this time there has been some braking action from the motor, so that by the time full magnetism is attained, the speed is less than 655 rev. per min. and the voltage never attains the value of 282 which was calculated.

When the time constants of the magnetic field and the absolute voltage and current capacity of a motor are well known it is possible to get results in braking which are far superior to the calculated conditions in Fig. 2. The retardation may be made much greater without overloading the motor in either current or voltage or kilowatt output. Fig. 5 shows the connections for a rack motor controller which gives power and dynamic braking in both directions of rotation. The resistance blocks

must be proportioned not only for smooth accelerating but for retarding in the proper manner to suit the motor characteristics.

For hoist service we have the choice of series, compound or shunt-wound motors. The conditions which affect the choice are voltage variation, amount of power available, height of hoist and time required for the trip. A voltage variation of 10 to 20 per cent is usual. The power supply is generally limited, or at any rate peaks are penalized. The height of hoist in some locations is as low as 40 ft. (12 m.) and in others as high as 180 ft. (55 m.). Time allowed for the hoist may be anywhere from 6 to 15 sec.

The hoisting speed is of course fixed by the distance and time. Where a low speed is used, the time of starting and stopping is unimportant, but for high speeds the time consumed in this way

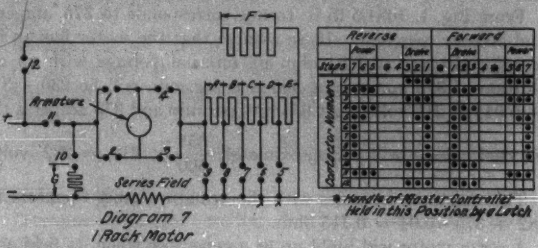


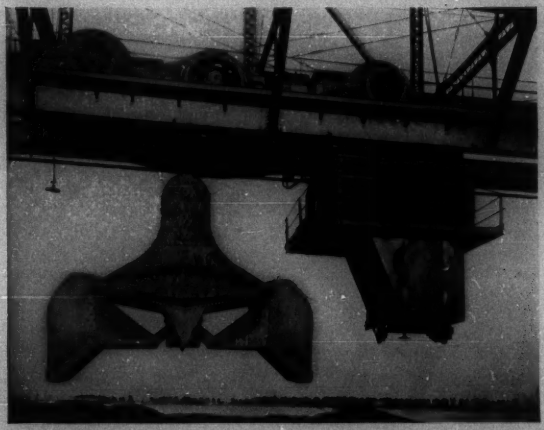
FIG. 5—CONTROLLER CONNECTIONS OF A SERIES-WOUND PROPELLING MOTOR ON A MAN TROLLEY COAL BRIDGE

is all-important. It is my opinion that a series-wound motor should be used for speeds of 360 ft. (110 m.) per min. or less if the height of hoist is such that at the speed used more than 8 sec. are consumed in the trip. For greater speeds and shorter time periods a compound-wound motor should be used. For still greater speeds of, say, 700 ft. (213 m.) per min. or more, a shunt-wound motor should be used. In order to present my ideas I will use two extreme examples.

Let us take a speed of 300 ft. (91.5 m.) per min., or 5 ft. (1.52 m.) per sec., a height of 40 ft. (12 m.) and a bucket which has 35 ft. (10.6 m.) of rope to be taken up while it is closing. It is possible on such a bucket to let the motor run at full speed while the bucket blades are in the act of coming together and the bucket is starting up; therefore no time is lost by running at re-

[MC LAIN]

FIG. 7—VIEW OF A MAN TROLLEY COAL BRIDGE SPANNING A COAL STORAGE PILE AND A BOAT



[MC LAIN]

FIG. 8—VIEW OF BUCKET AND TROLLEY USED ON BRIDGE IN FIG. 7.

duced speed from the time the motor attains full speed in starting to close until the bucket is fully hoisted. If a shunt motor were used, 1.5 sec. would be required to start, 1 sec. to stop and 13.75 sec. would be required for full-speed running to wind up the whole seventy five ft. (22.8 m.) of rope. This makes a total of 16.25 sec. to make the trip. If a series motor were used, the same time would be required, except for the fact that while the bucket is being closed the load on the motor is small and the motor speeds up. The motor will run about 30 per cent above normal speed for most of the closing period, but toward the end of this period the load increases and the speed comes down to normal. About one second is saved by the series motor on each trip. Therefore the shunt motor would have to be geared for 6 per cent more speed in order to make the trip as quickly as the series motor, and would take 6 per cent more power while hoisting at full speed. Automatic current limit control is used on these motors; and since, at times, it is necessary to start the bucket from midair, the relays must be set for a current which will be great enough to start the loaded bucket even at the lowest line voltage. No more than this current is required, because the time of starting is unimportant. When a relay drops and a contactor short-circuits a block of resistance, there is a consequent current peak. For a given number of contactors, the ratio of these current peaks to the current at which a relay drops is at least 10 per cent more for a shunt than for a series motor. Furthermore, the current at which a relay drops must be made greater on a shunt motor, because, on low voltage and consequently weakened field, more current is required for a given torque than is required on a series motor whose field strength is not affected by voltage variation. On 80 per cent of normal voltage the current in a shunt motor may increase as much as 10 or 20 per cent. Summing up the above statements, we see that the starting current on the shunt motor will be about $(1.06 \times 1.10 \times 1.15 =)$ 1.34 times the starting current on a series motor. The series motor has the further advantage that when the bucket is not digging much coal and the weight is reduced, the speed will increase. Another advantage is that the series motor can stand the rapid voltage fluctuations with no damage, while a shunt motor may be damaged.

On high hoist speeds all of the advantages mentioned above for the series motor disappear, and a very decided advantage appears for the shunt motor. At these high speeds it is import-

ant that the full hoisting speed be as nearly constant as possible, regardless of voltage or load. The speed of a series motor may vary at least 30 per cent more, under service conditions, than that of a shunt motor. If the speed is say, 15 ft. (4.57 m.) per sec., 30 per cent variation means 4.5 ft. (1.37 m.) per sec. An operator cannot be expected to hoist to the correct height under such conditions without wasting considerable time running at low speed just before stopping at the top. Another advantage of the shunt motor is that it is very easy and simple to provide dynamic braking for stopping at the top so that no time need be wasted in getting stopped.

Let us take the example of 900 ft. (274 m.) per min. or 15 ft. (4.57 m.) per sec. speed, and 90 ft. (27.4 m.) height. A shunt motor will close the bucket as quickly as a series motor because the bucket will not dig properly if either motor runs at full speed. It is necessary to slow down or stop just as the bucket blades close, because the speed is so high. In order to make it worth while to use such a high speed, not over 3 sec. can be allowed for accelerating. This means that a rate of 5 ft. (1.52 m.) per sec. per sec. is used for acceleration or an extra pull of 15.5 per cent on the bucket. About 15.5 per cent additional pull is required to accelerate the drums and gears. In most cases a torque equivalent to 50 per cent of the pull on the bucket is required to accelerate the motor armature. The total torque required for accelerating in 3 sec, and for hoisting is therefore 181 per cent of the torque required for hoisting alone. In order to accelerate so quickly the current relays must be set to drop down at 145 per cent of the hoisting current. This is so high above normal that even on 80 per cent voltage the motor will start and therefore no extra current peaks are encountered, as would be the case on a low-speed hoist. There would, however, be greater peaks of current caused by the short-circuiting of the starting resistance, unless the field were made especially strong for starting and then reduced to normal strength during full speed running. An increase of speed due to a light load is a disadvantage on such a high speed because it deceives the operator and causes mistakes in the height to which the bucket is hoisted. A motor which has enough reserve capacity on its commutator to stand the 81 per cent overload encountered at starting will not be liable to much damage from fluctuating voltage, and therefore no extra cost need be put into the motor to make it stand this condition.

As mentioned above, it is advantageous to stop at the top with

dynamic braking on a high-speed hoist. If the motor is geared directly to its load the combined motor and load, for the case of 900 ft. (274 m.) per min. speed above stated, would coast (0.81 × 3 =) 2.43 sec. after power is shut off, and in this time would travel (2.43 × 15 ÷ 2 =) 13.2 ft. (4 m.) One second of this time could be saved by waiting till the bucket is within 7.5 ft. (2.3 m.) of the top and then applying full capacity of the motor as a brake by connecting resistance in parallel with the armature. Such an arrangement has other practical advantages. For example, if the bucket is just starting out of a boat and is about to strike a hatch coaming, it is imperative that an easy means of making a quick stop be at hand.

It is common practise on low-speed hoists which use series motors to lower the empty bucket by dynamic braking. All

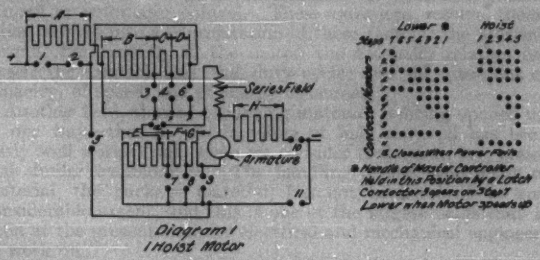


FIG. 6—CONTROLLER CONNECTIONS OF A SERIES-WOUND HOIST MOTOR ON A COAL BRIDGE

that is needed is to determine the torque on the motor shaft by making mechanical calculations. Find the current which flows in the motor, when this torque is exerted, by referring to the motor curve. Provide a rheostat in series with the armature and series field of such value that voltage drop in the rheostat with necessary current flowing will be equal to rated voltage of the motor. Many motors can stand more than rated voltage under this condition, because the current is relatively small. Thus the lowering speed can be much more than the hoisting speed. However, when this resistance is short-circuited to stop the motor, there is a large current peak which causes an increase in the motor voltage before the speed is actually reduced, because the current peak over-excites the field. It is, therefore, necessary to do this short-circuiting in several small steps, else

the momentarily high voltage, current and speed will cause damage on the commutator. Fig. 6 shows controller connections for such a motor. Resistance blocks *E*, *F* and *G* are proportioned for the uniform acceleration of the motor under load. Blocks *C* and *D* are added to give total resistance sufficient for lowering at high speed. This particular controller is arranged to give a limited amount of power to the motor in a lowering direction for the purpose of accelerating the motor quickly when the bucket is being opened.

Electricity for coal and ore bridge operation is now a necessity. No other form of power is capable of being transmitted so readily to the place where it is needed for use. Electricity has proved to be far cheaper than steam for this purpose. Practically all of the unloading of boats on the Great Lakes is done with electric power

DISCUSSION ON "DIRECT-CURRENT MOTORS FOR COAL AND ORE BRIDGES" (MCLAIN), DETROIT, MICH., JUNE 23, 1914.

D. B. Rushmore: There is a fairly sharp dividing line which distinguishes motor application work from other fields of engineering, except railway work, which must be considered as a specific field in itself. The field of motor application is very largely that of driving machines which either perform work themselves or are very actively connected with the work performed, and machines engaged in conveying material.

In every case of motor application the first thing we start out with is the duty cycle, the load curve of the work to be performed. Then we have, after proper consideration has been given to the subject, all the different electrical motors available, the selection to be determined by the characteristics of the machine involved. These are the two things which have to be fitted together, and with them goes also the question of controller, hand control or automatic control. These questions resolve themselves always into a consideration of these factors: the starting torque, the heating of the motor, the necessary relation between the control and the duty cycle, and the questions of capacity, of speed, and of energy consumed.

Another field, that of conveying material, is being opened up in one way—that is, the handling of bulk material has been fairly well worked out, when we consider coal, sand, ore, grain, and similar commodities. The handling of the other class of material, the package material, has not been solved to any considerable extent, and this is one of the largest fields that is open at the present time for electrical and mechanical engineers to work on.

It is very interesting to see how the different factors involved in the class of problems dealt with in Mr. McLain's paper change in the order of their importance. With a big ship waiting to be unloaded, speed might become a more important factor than any other consideration, and in conjunction therewith the factor of proper speed control in order to obtain the maximum capacity. In other cases, where the energy consumed is very large and the cost of power a considerable proportion of the cost of the final product, the problem would be considered from a different viewpoint.

S. C. Lindsay: I ask the author whether we are to infer that braking has usually been accomplished by electrical means, or whether they have tried out and discarded frictional brakes operated by air or magnetic devices.

T. E. Tynes: Some very interesting control problems come up in connection with ore bridges. We have on our bridges two 230-h.p. motors which are used not only to hoist, but to move the bridge back and forth, down the track, over the different piles of ore. We run the bridge up and down the track with the motors in series. On the hoist we use them in parallel,

or multiple. We use dynamic braking on the lowering, but with only one of the motors on dynamic braking, *i.e.*, having only one motor perform the dynamic function. We had to do some scheming to get the arrangement of contactors which would allow us to hoist in multiple, and also use dynamic braking with one motor, but it can be done, and done very nicely.

R. H. McLain: In all large hoists of 5-ton bucket capacity and greater, I think I am perfectly safe in saying that dynamic braking is used, for the reason that friction brakes large enough to stand the wear and tear would take up too much room and be too expensive to maintain. That seems to be the present attitude of those designing these bridges. For smaller hoists this is not so generally the case. It is sometimes a matter of opinion, but I believe the most popular way is to use dynamic braking. Sometimes dynamic braking is used on the hoist motion alone and not on the racking motion, and at other times on both motions. The present status of the art was arrived at by a lot of trials with various ways of handling brakes. Of course, on hoist motion they always have mechanical brakes to sustain the load, but not necessarily to lower it.

Presented at the 31st Annual Convention of the American Institute of Electrical Engineers, Detroit, Mich., June 23, 1914, under the auspices of the Industrial Power Committee.

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METHODS OF KEEPING DOWN PEAKS ON POWER PURCHASED ON A PEAK BASIS

BY T. E. TYNES

ABSTRACT OF PAPER

The author mentions two general ways of reducing peaks, the first being to furnish the peak power from a separate source such as a local steam turbine, and the second to store some of the power furnished by the power company, which is given up later when the peak demand comes on. In the case of the plant described by the author a mixed pressure turbine was installed to take the peaks, this being selected on account of available exhaust steam from pumps, air compressors, etc. The turbine is direct-connected to two direct-current generators mounted on a common bed-plate. The first plan tried was to use a motor-driven rheostat operated with clutches which in turn were operated by solenoids energized by current controlled by a contact-making ammeter.

After the installation of a maximum demand meter which integrates the one-minute peaks, the rheostat control was found to be too slow and a special peak-taking device was then installed. This device consists of a rod carrying points which successively make contact with mercury cups and which is operated by the moving element of the graphic meter. These mercury contacts close relay circuits which operate to short-circuit sections of resistance in the field rheostat of the turbo-generator, raising its voltage, and also cut in sections of resistance in the field rheostat of the motor-generator set, weakening its field and thus reducing its load.

THE BENEFICIAL results to be obtained by maintaining a good load factor are so well known, both to the producer and purchaser of power, as scarcely to need mentioning. From the producer's standpoint, the increased generating capacity made available, the better regulation obtained on the generating apparatus, and lower maintenance costs on generating apparatus due to absence of shocks from violent fluctuations of load, give results that are well worth striving for.

From the consumer's standpoint, especially those who pay on a peak basis, a high load factor is very desirable in that they receive more power for a given sum of money; or, in other words, their rate per horse power-hour or horse power-year is decreased.

There are several ways in which these desirable results can

be obtained by consumers of purchased power. They may be grouped under two general methods:

In the first method, the power demand represented by the peak is furnished from a separate source, such as a local steam turbine, hydroelectric or gas-engine-driven plant.

In the second method, the power required of the peak was previously furnished by the power company and stored by the purchaser to be given up later when the peak demand comes on. This storing of energy may be accomplished either by means of storage batteries, or, in case of frequent peaks of short duration, by means of heavy, rapidly revolving flywheels.

It is to be noted that in the second method the average demand on the power company is higher for a given total energy consumption by the purchaser than in the first method.

In the Institute TRANSACTIONS for 1911 a method of lopping off peaks on power furnished to ore bridges is described* by Messrs. Motter and Tatum. The results are accomplished by means of a d-c. machine on the shaft of which is mounted a flywheel. This flywheel set floats across the line and is either absorbing or giving up energy, according to the demands of the circuit to which it is connected, and may be called an electromechanical storage battery. By a suitable arrangement of relays and switches the set absorbs energy when the demand on the circuit is below a predetermined amount and gives up its stored energy when the demand on the circuit exceeds this amount.

In the following pages the writer will briefly describe a method by which an improved load factor was obtained on purchased power.

Some exhaust steam being available from hydraulic pumps and air compressors in the power house of the company with which the writer is connected, it was decided, after studying the conditions carefully, to install a mixed pressure turbine to take peaks, so as to get a more uniform load factor on the purchased power. The latter is delivered at 60,000 volts and stepped down to 2300 volts. At this voltage the greater part of it is used to drive synchronous motor-generator sets, and the remainder is further stepped down to 440 volts and used to drive three-phase induction motors.

As the greatest fluctuations and largest demand came on the

Flywheel Load Equalizer, TRANSACTIONS A. I. E. E., XXX, 1911, page 729.

FIG 1 [TYNES]

FIG. 2 [TYNES]

FIG. 3 [TYNES]

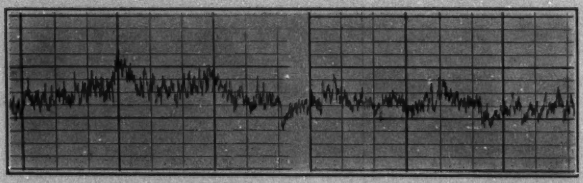

FIG. 7 [TYNES]

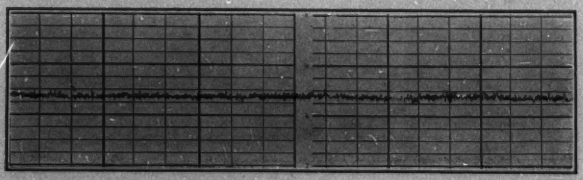

FIG. 8 [TYNES]

d-c. side of the motor-generator sets, it was found to be more efficient to generate direct current directly rather than generate alternating current and convert it to direct current through the motor-generator sets, a saving of at least 16 per cent being effected.

Accordingly a 750-kw. mixed pressure d-c. turbine unit was purchased, views of which are shown in Figs. 1, 2 and 3. The turbine is direct-connected to two 375-kw. 250-volt commutating-pole four-pole generators driven at 1500 rev. per min., all mounted on a common bedplate. The generators are mechanically coupled in tandem and electrically coupled in parallel. Each machine is complete in itself, so that if one machine fails the other can deliver its full output, making 50 per cent load on the turbine.

Power is purchased on the basis of the one-minute peak. At the time the turbine installation was planned, the one-minute peak was measured by a scale, the height of the peak being the point at which the one-minute space would just come within the boundary of the peak, shown by *A*, Fig. 4.

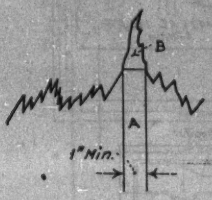

FIG. 4

The turbine would naturally respond to a change of load more quickly than the other apparatus, but would not, unassisted, take all the peak that it was desired that it should; therefore a motor-driven rheostat was furnished (Fig. 5), with two faces, one for each generator on the turbine. The small motor runs continuously, transmitting its power to a shaft at right angles to it. On this shaft are two clutches, one half of each of which is fastened on the continuously running shaft. The other half of each clutch is connected through gearing to the rheostat arms in such a manner that when one of the clutches is engaged the arms on the rheostats revolve clockwise and when the other clutch is engaged the arms rotate counter-clockwise. The clutches are interlocked so that only one can be in at a time. The clutches are operated by solenoids energized by current controlled by a contact-making ammeter.

About this time the power company perfected a maximum demand meter which integrates the one-minute peaks. They installed this instrument in our substation, with the result that our peaks jumped up from 8 to 12 per cent above those

previously obtained on the same load, due to the portion B, Fig. 1, being added by the integration, which by the scale method of measurement was not taken into account. Our load factor was of course lowered proportionately. This put us on our mettle to try, if possible, to regain our lost load factor.

We found the rheostat method of control too slow, as every second counted on that integrated peak, so we tried another

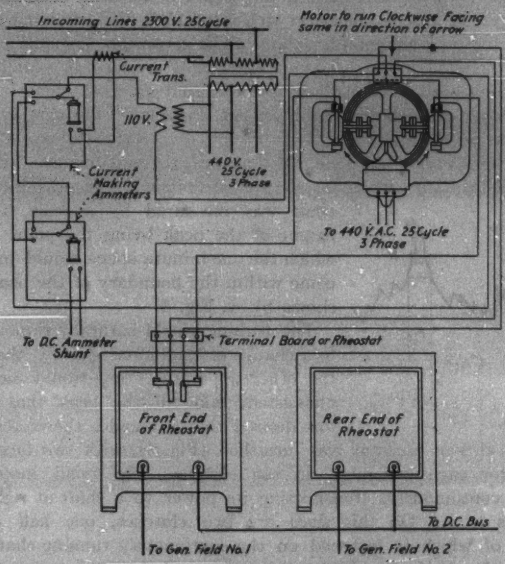

FIG. 5—CONNECTIONS OF TWO RHEOSTATS OPERATED BY SINGLE SHAFT WITH CONTACT-MAKING AMMETERS

scheme of control which is illustrated in Fig. 6, a description of which follows:

The piece A consists of a metal rod with three points, p_1, p_2 and p_3, projecting downward over the centers of three cups partly filled with mercury. p_1 is shorter than p_2 and p_3, which are the same length.

A is raised and lowered by the moving element of a graphic

recording wattmeter, which serves the double purpose of operating the peak-taking device and making a visible record of the load.

The points p_1, p_2 and p_3 are so adjusted that when the load reaches the predetermined amount at which it is desired it shall be held, the points p_2 and p_3 just touch the mercury, closing the circuit through the operating coil of contactor $C\,T_1$, which closes, short-circuiting a section of resistance in the shunt field rheostat of the turbine, raising its voltage and causing it to take more load. When $C\,T_1$ closes, it opens a relay in the circuit of the operating coil for contactor $C\,M_1$, which causes the latter to open, cutting in a section of resistance into the shunt field rheostat of the motor-generator set, weakening its field and reducing its load.

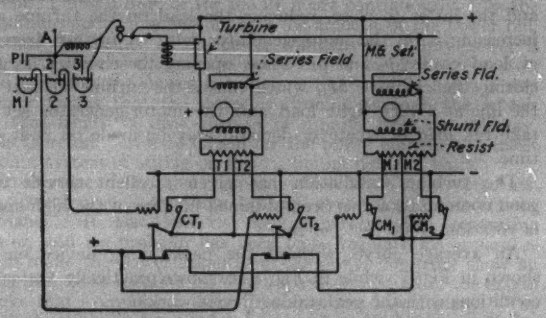

FIG. 6—DIAGRAMMATIC SKETCH OF PEAK-TAKING DEVICE

If the reduction of the load on the motor-generator sets and the increased load on the turbine is not sufficient to keep the peak down to the predetermined amount, the points p_1, p_2 and p_3 will be still further lowered, allowing p_1 to come into circuit, closing contactor $C\,T_2$, cutting more resistance out of the shunt field circuit of the turbine and cutting more resistance into the shunt field circuit of the motor-generator sets, causing a further increase of load on the turbine, and decrease of load on the motor-generator sets.

In order to protect the turbine from excessive overloads, a shunt is inserted in the positive leads of the turbine generators. The current around this shunt operates a contact-making ammeter, which opens and closes the circuit to the mercury

cups. It is adjusted to open the circuits at 50 per cent overload on the turbine. When the turbine reaches this load, any further increase in its load causes the contacts to part, opening the control circuit to contactors $C\,T_1$ and $C\,T_2$, which opens, and in opening closes the contactors $C\,M_1$ and $C\,M_2$. The result of these operations is to decrease the load on the turbine and increase it on the motor-generator sets until the turbine load falls below its overload limit. When this is reached the contactors $C\,T_1$ and $C\,T_2$ again close and $C\,M_1$ and $C\,M_2$ open, this action of the contact-making ammeter being similar to a voltage regulator.

When the load reaches the point below which we do not want to take peaks, the point p_1 is raised, breaking the circuit through contactor $C\,T_2$ and $C\,M_2$, causing the former to open and the latter to close, reducing the load on the turbine and increasing it on the motor-generator sets. A further decrease of load causes p_2 and p_3 to rise, opening the circuit $C\,T_1$ and closing the circuit $C\,M_1$, which causes the turbine to float on the line at a very light load and the motor-generator set to take full load or whatever demand may be made on it at the time.

The turbine installation has given excellent service and good commutation has been obtained in spite of the high speed of rotation (1500 rev. per min.).

An average curve, without the peak-taking device on, is shown in Fig. 7, while in Fig. 8 are shown practically the same conditions with the peak-taking device working.

DISCUSSION ON "METHODS OF KEEPING DOWN PEAKS ON POWER PURCHASED ON A PEAK BASIS" (TYNES), DETROIT, MICH., JUNE 23, 1914.

Rudolph Tschentscher: Power contracts, as you all know, are usually made on a peak basis, and the question of the reduction of these peaks is a most important one. I believe it is desirable to emphasize the point Mr. Tynes has mentioned, namely, that the reduction of peaks is of material benefit to the power generating company.

Paul M. Lincoln: This point that Mr. Tynes has raised is an exceedingly important one. Wherever power is taken from a hydraulic plant, the maximum demand method of charging is a logical one; no question about it. This is particularly true in the case of the hydroelectric plant where the water is not limited, such as the Niagara Falls plant. It does not matter to the power company whether the power is taken for 15 minutes, or one minute a day, or for the 24 hours continuously, it is the maximum demand which dictates the amount of the power bill, because the ability of the power company to supply power is limited by the output of the prime mover or of the generator. The fact that the power is taken continuously 24 hours a day merely means that the water is running through the wheels for that length of time, instead of running over the spillway. It is therefore perfectly logical for the power company to insist upon a system of selling on the maximum demand basis.

In the case of the steel company which Mr. Tynes represents, its power curve is anything but an even line of continuous demand. It also has its own apparatus for generating power, and his problem has been to so regulate his apparatus as to make the power taken from the power company show an even line, to so regulate his own apparatus that all of the excess above that even line is taken from his own steam plant. The method which he has used to secure that result is exceedingly interesting, and one of very great value.

J. Lester Woodbridge: This paper presents a special solution of a problem which undoubtedly exists very commonly in districts where power is purchased on the maximum demand basis. It would, perhaps, be interesting to compare the results obtained by this solution with those which might have been obtained by the application of a storage battery, but the data given in the paper are hardly sufficient to permit of such a comparison being made. Doubtless the solution adopted in this particular case was the wise one in view of the presence of exhaust steam which, I presume, was obtained without additional cost. The paper, however, does not give us the length or the height of the peak very definitely.

It would be interesting to have the financial results set forth in this paper as well as the technical results; for example, whether the operation of this turbine actually costs anything for fuel, that is, whether the steam was supplied without additional cost for fuel,

whether the exhaust steam was sufficient to operate the turbine, or whether some live steam had to be used; also whether the cost of attendance was increased. In fact, the total cost of operating the plant would be an interesting item, so that we might compare that with the saving effected. Possibly these figures might be added by the author in a subsequent discussion.

It would also be interesting to know the total power produced by the mixed turbine and the cost per kilowatt-hour to produce it. It also occurs to me to ask whether, if the power is obtained without cost by utilizing exhaust steam, the investment for the installation having once been made, it would be economical to operate this outfit to handle more than merely the peak load. Could it be operated 24 hours a day to take some of the body of the load itself, if it does not cost anything to operate? A number of these questions could perhaps be very interestingly discussed in an addition to the paper.

J. R. Bibbins: Considering this paper from the standpoint of the central station, I notice from Fig. 4 that a one-minute maximum is the basis upon which this system depends. It seems to me that the economic value of this whole peak-reducing apparatus depends greatly upon what duration of the peak is incorporated in the power contract. I have in mind a railway load in which the maximum demand is over 100,000 kw. The power contract involves a fixed rate primary or readiness-to-serve charge, proportioned to the maximum demand of an hour's duration (averaged over three successive days), and a secondary or service charge, dependent upon the output of the station, and with a sliding scale of rates per kilowatt-hour. This works out as follows: During the summer the maximum peak loads are very largely reduced, but the railway company continues paying for the maximum one-hour demand of the previous winter, and logically so, throughout the entire year. If a mild winter happens to occur, in which the heating and the additional friction load is reduced, these two factors combine to reduce the maximum peak and primary charge.

Now, the point that interests me here is the use of this one-minute maximum, and if we analyze a railway load it is very clear that the actual peak upon which such a primary charge depends is not always of as long duration as stated in this contract, *i.e.*, one hour. And so it occurs to me that there is a possibility of applying a shorter maximum period in power contracts for such large systems with primary charge adjusted in accordance with the relative overload capacity of the station. Referring back to the prime mover, it is very clear that, with the very large units now used and the great overload capacity available within reasonable limits of temperature rise, if we had a shorter maximum period than one hour the primary charge upon which it is computed might be considerably less than it is to-day.

In this particular case the contract worked out in a very

peculiar way. As the system expanded and the power load built up, it was found that the primary charge kept ahead of the secondary charge, with the net result that the total cost per kilowatt-hour actually increased as the power consumption of the railway increased. It seems rather illogical that with a load increasing from 60,000 to 100,000 kw. the net cost of power per kilowatt-hour, including these two factors, primary and secondary, should have risen under conditions of such an extremely large output. One explanation will occur, from the fact that any considerable improvement in the service of street railways necessarily means more service at rush hours. In fact, the street railway problem is almost entirely one of rush hours, and the additional equipment operated at the rush hours must necessarily increase the maximum demand for that period. So that as we demand from our street railway companies improved service, we must suffer a decrease in load factor and a higher primary charge.

I take it that from the prime mover end, there is little hope for the development of a special type of apparatus, other than the turbo-generator outfits that we already have, which would automatically absorb these high peaks, with the single exception of the combined hydraulic and steam power system which Mr. Lincoln mentioned.

So the specific question I raise, from the central station standpoint, is, whether this shorter period mentioned in this paper would not be equally as applicable to central station conditions as to the industrial load that is here described, *i.e.*, whether a one-hour maximum is entirely justifiable in cases where the real maximum for which the central station must provide apparatus is considerably less than one hour; in other words, whether we cannot take advantage of that fact and reach a more logical primary charge, so that the occurrence of a very short peak load occasionally, of considerably higher maximum than the hour would average, (but well within the momentary capacity of the equipment), will not become such a burden as it does in this case. Obviously, the shorter the duration of peak, the greater the margin of safe overload available from a given investment, and usually, in railway loads, the exaggerated peaks are of very short duration.

R. H. McLain: I would like to say a word about this matter of charging for peaks, based on one example that I am familiar with. There is a large number of coal docks and a street car load, all of which make up a very large part of the central station power load, and there was, before many coal docks began to buy power, a great deal of argument about how to charge for this power. In the beginning, the coal docks were charged on an instantaneous peak basis—that was the primary charge for them. As the coal docks increased in number, the load curve for the central station company became flatter and flatter. I do not know how they charge for the power now, but I know

enough about the system to know that it would be practicable for them to charge for five-minute peaks, or some other peak like that, and not take any account whatsoever of these one-second and one-minute peaks. I think that the central station companies should take a very broad-minded view of this situation, and when they serve a lot of power consumers should try to keep from putting the customer to a great deal of expense in cutting down his peak, when another customer across the road, or two or three more, might combine with this first customer in such a way as to make the entire load almost uniform. I firmly believe that the more the central station companies take this view into account in making their charges, the more popular will be the use of central station power; but, of course, for any one location the particular nature of the load should be taken into account.

E. D. Dreyfus: The ingenious method employed by Mr. Tynes to maintain a practically uniform load upon the power company's system has impressed me very much. No doubt Mr. Tynes has been able to effect a certain degree of economy in the operation of his plant which is probably due to fortuitous conditions such as the availability of an exhaust steam supply and the presence of operatives who can well afford to take care of the extra equipment necessary in addition to looking after their other duties. The situation is manifestly exceptional and therefore we should be careful that the idea does not become prevalent that the scheme described is possible of broad application.

According to my conception of the problem and from many investigations made in this direction, the trend of results tends to show that it is the low load factor business upon which the central station can most readily compete with the isolated plant. This is largely true for the reason that the so-called "stand-by" cost of the isolated plant (including capital charges, labor, banking and discrepancies) plays an important part in the total cost under low load factor conditions.

When operating at high load factors, these "stand-by" charges are spread over a large number of kilowatt-hours and therefore the unit cost is very rapidly reduced. I believe this can best be shown diagrammatically, and the accompanying illustration (Fig. 1), in which values are taken from a case selected at randon, will aid in establishing the truth of the proposition.

Obviously the comparative showing will in each case depend upon the assumptions made. There is a wide range in the operating results of different isolated power plants, naturally depending upon their equipment and the ability and faithfulness of the operating force. Two limits (one shown by heavy solid lines and the other by heavy dotted lines) for the isolated power plant operation are given so that this phase may be duly regarded. On the other hand, the cost of central station power for fixed

conditions is fairly uniform in the different geographical divisions of the country, and consequently a single line of costs has been included for central station power (shown by the heavy dot and dash line).

Hence, due to what may be termed the inherent slope of the total cost lines or curves, the relative rise with load is actually

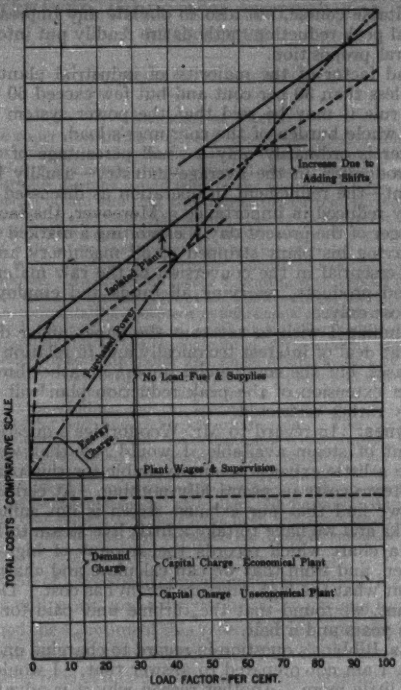

FIG. 1

in favor of the isolated power plant, and, as here indicated, the larger independent plant may show lower costs at points beyond 50 to 75 per cent load factor, provided all other handicaps have been overcome. While this argument is of a general nature it is sufficiently specific, I believe, to prove that unless the peak can be reduced by flywheel effect or by virtue of

some peculiar local conditions, the cost of attempting it can hardly be justified.

The large and increasing number of industries committed to the use of purchased power, and representing over 33 1/3 per cent of the electric power used in the manufacturing industries in the United States, prompts the exposition of these facts not only to confirm that "out-and-out" purchase is usually the most profitable course, but also to obviate any impression that economical peak reduction methods are readily put into practise as a general proposition.

The load factor of the majority of industrial plants is considerably less than 30 per cent and but few exceed 60 per cent, and as a rule it may be said that the power system can best carry the whole burden of the consumer's load.

As power is ordinarily only a small percentage of the total cost of production in the average industry—usually less than 10 per cent—the refinement in operation as discussed is correspondingly reduced in importance. Moreover, the factory and mill manager of the present day is exhibiting a marked tendency toward having his plant stripped of all machinery and equipment non-essential in the conversion of the raw materials into the finished products, reserving all funds and employment to that purpose only.

In concluding I wish to say that the paper under discussion is of a great deal of interest technically and in relation to a few isolated cases, but the commercial import is rather limited and the further extension of the peak reduction plan will be in all probability rather restricted.

T. E. Tynes: In regard to Mr. Woodbridge's question as to the amount of steam available, I would say that we usually have quite a little exhaust steam available for this purpose, so that our steam costs us practically nothing. At certain times, however, we find that our exhaust steam is not sufficient for heavy peaks and we have to take a little live steam to help out. We have a chart which records the amount of high-pressure steam taken, and from that we can calculate and charge to the turbine unit what the high-pressure steam has cost. Deducting that amount, we found that the turbine unit paid for itself in about two years and a half.

As to Mr. Bibbins's question in regard to charging on the one-hour peak, I am not prepared to answer that. I would like to study it a little more. Another reason why it is advantageous to us to keep down our peak is that we are allowed a certain limit above what is called our firm power; any amount in excess of that is added to our firm power, and we have to pay for that until the next period of readjustment.

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CONCATENATED INDUCTION MOTORS FOR ROLLING MILL DRIVE

BY WILLIAM O. OSCHMANN

ABSTRACT OF PAPER

The paper describes a six-speed concatenated induction motor set for driving the finishing rolls of a 12-stand continuous mill. Analysis of the conditions in this mill showed that the use of a low-pressure turbine would lead to the waste of a large amount of exhaust steam and that the alternating-current turbine plant which was in operation had ample reserve capacity for driving the mill. The large number of speeds required suggested the use of a direct-current motor, but as this required a motor-generator set it was found to be more expensive than the concatenated motor. An induction motor operating with a speed regulating set was also considered, but its disadvantages lay in the fact that a commutating motor or synchronous converter would be required, the performance of which at the frequency employed was questionable. The concatenated set installed consists of a double-wound main motor and single-wound secondary motor, both stators mounted on a common bed-plate and both rotors on a common shaft. The larger motor has both a 14- and 16-pole stator winding and the secondary motor has its winding arranged for four- and eight-pole connections. The control system is described in detail; its operation is very simple, so that no regular attendant is needed. The motor has six definite speeds and two additional resistance speeds, and while the control is somewhat complicated it has been made so nearly foolproof as to make a special attendant unnecessary. As a result of the year's operation there have been but three interruptions, the total loss of time due to which has been 68 minutes.

THE USE of a six-speed concatenated induction motor for rolling mill work, and a discussion of the various factors which determined the selection of this type of drive, and the results obtained, will no doubt be of interest. This motor is used to drive the finishing rolls of a twelve-stand continuous mill. The output of the mill consists of round steel rods ranging from 23/64 to 1½ in. (9.1 mm. to 38 mm.) in diameter, also small flats, squares and special sections. The former general arrangement of this mill is shown by Fig. 1.

The two heating furnaces are of the continuous type, the billets being conveyed from the furnaces at *A* to the roughing rolls of the continuous mill at *B*, by a chain-driven roller conveyer.

The roughing stands are twelve in number, all two-high, and are driven through spur and bevel gears by a 44 by 60-in. (112 by 152-cm.) simple non-condensing Corliss engine, running at about 65 rev. per min. average speed. The number of roughing stands used depends upon the size of the finished bars. In rolling some of the larger sizes, but six or eight of the twelve stands are used.

From the roughing stands, the bars are delivered through pipe conveyers to the finishing rolls. These are four stands of two-high 11-in. (28-cm.) diameter rolls, and were formerly belt-driven by a 28 by 36-in. (71 by 91-cm.) simple non-condensing engine, running at speeds varying from about 85 to 145 rev. per

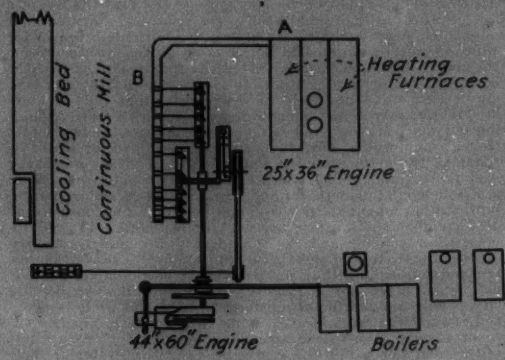


Fig. 1

min., the engine and mill speed being adjusted to suit the size of material rolled. Changes in roll speed were obtained by varying the engine speed, the engine governor being driven through friction disks, thereby allowing the engine speed to be readily changed.

The engine belt wheel was 218 in. (554 cm.) in diameter, the mill pulley 65 in. (165 cm.) in diameter, giving about 3.35 to 1 speed ratio, thus giving a speed range on the rolls from about 285 to 480 rev. per min. All four stands of rolls are used on this mill for practically all sizes; on certain sections, however, but two stands are used.

Steam for operating the engines was obtained from the

boiler plant shown in Fig. 1, consisting of two boilers equipped with chain grate stokers, and three hand-fired boilers. The other mill equipment consists of a rope-operated cooling bed, shears, scales and rod coiler.

The extreme speed range of 285 to 480 rev. per min. on the finishing stands of this mill is directly due to the inability to roll 1½-in. (38-mm.) rods at a higher speed than 300 rev. per min., or to secure sufficient tonnage of the small sizes without a higher speed, the large number of sizes rolled making impossible the ideal mill arrangement of a single-speed mill, rolling a practically constant-size product.

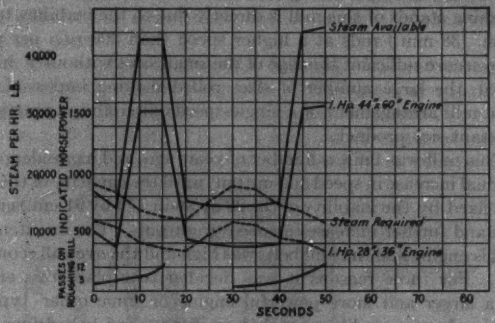
This mill was built a number of years ago, and has undergone a gradual increase in speed and output, until the capacity of the mill was fixed by the inability of the 28 by 36-in. (71 by 91-cm.) engine to stand further increase in speed or output. The maintenance of this engine and the mill belts was high and the over-all economy low. For these reasons it was decided to replace this engine by a larger and more powerful engine or some other type of drive. It was readily seen that an engine and belt-driven mill at a higher speed would not be desirable (the belt speed of the 28 by 36 in. engine being about 8000 ft. (2440 m.) per min. when rolling the small sections and it being impracticable to reduce the size of the mill pulley). An engine with a gear or rope drive had a higher first cost than a motor-driven mill, also a larger figured operating cost due principally to about 25 per cent higher coal cost at the mill than at the steel company's central power plant.

This mill presented some very interesting features: first, the different speeds required; second, the fact that the steel company had an a-c. turbine power plant with ample reserve capacity for driving the mill; and third, that the exhaust steam from the 44 by 60-in. (112 by 152-cm.) engine seemed to offer an ideal exhaust steam turbine location.

Tests were made on both mill engines in order to determine the power requirements of the finishing rolls and the exhaust steam available from the 44 by 60-in. engine, also the time relation between the power requirements of the finishing rolls and the steam supply from the 44 by 60-in. engine.

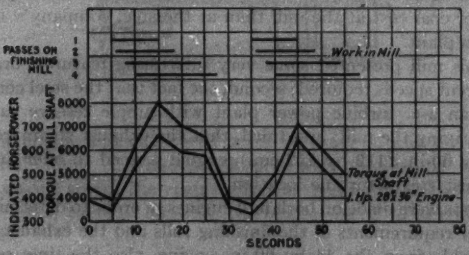
These tests were made by taking simultaneous continuous indicator cards on both engines, the mill speeds and the work in both mills being observed at the same time. Several tests on different sizes were made. The results of some of these tests are shown in Curves 1 to 19.

Curve 1 is for ⅜ in. (9.5 mm.) diameter round rods, and shows the horse power of each mill, also the exhaust steam available from the 44 by 60-in. engine, and the steam required by an exhaust steam turbine to drive the finishing rolls. These tests



Curve 1—⅜-in. Rounds.

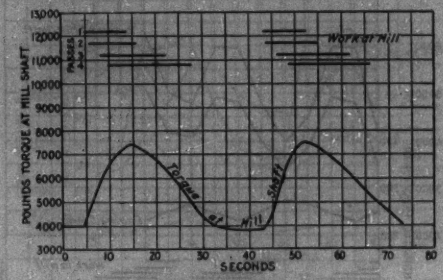
showed that sufficient steam was available, but that a small regenerator would probably be necessary. Tests on this size gave about 500 h.p. as the average power required and also showed a maximum mill speed of 472 rev. per min., and an



Curve 2—⅜-in. Rounds.

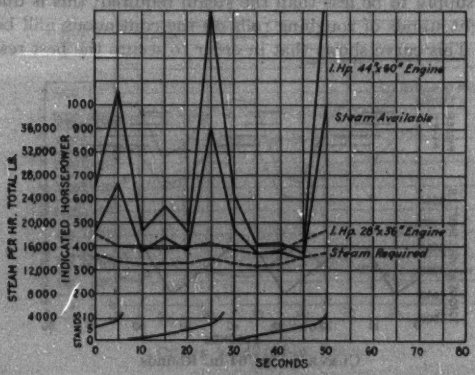
average speed of 462 rev. per min. Curve 2 is for a test of the 28 by 36-in. engine on this size. These tests show a peak torque of about 8000 lb. (3630 kg.). The maximum steam demands are greater than the minimum steam available; the periods of insufficient steam supply are extremely short. Curve 3 gives

the calculated duty cycle at the maximum mill output, the effective torque being 6000 lb. (2720 kg.), the h.p. 545, and the peak h.p. about 635.



CURVE 3—⅞-in. Rounds

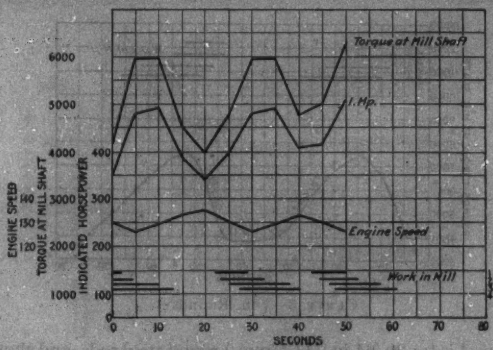
Curve 4 is for 29/64-in. (11.5-mm.) round steel rods, and shows an abundance of exhaust steam. The maximum mill speed on this size was 456 rev. per min. and the average about 442 rev.



CURVE 4—29/64-in. Rounds

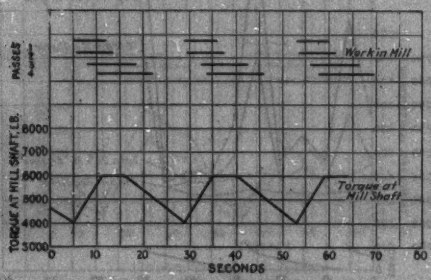
per min.; the r.m.s. horse power was 425. The peak torque was about 6000 lb. (2720 kg.), and the peak h.p. about 500. Curve 5 is for a test of the 28 by 36-in. engine on this size. Curve 6

gives the calculated duty cycle at the maximum mill output, the r.m.s. torque being 5400 lb. (2450 kg.), the h.p. 488, and the maximum horse power about 573.



CURVE 5—29/64-in. Rounds

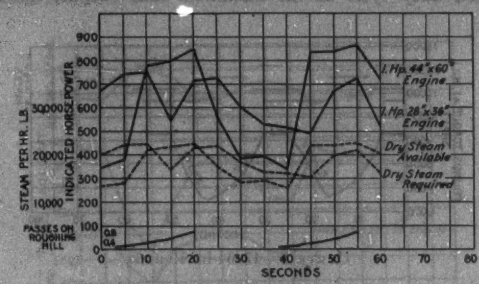
Curve 7 is for 47/64-in. (18.6-mm.) round rods, and shows the steam supply to be less than the steam required; this is due to but eight stands of roughing rolls on the continuous mill being used. This curve shows that in order to secure the best results



CURVE 6—29/64-in. Rounds

a mixed-pressure turbine and a small regenerator would no doubt be necessary. On this test the maximum mill speed was 448 rev. per min., the average 432 rev. per min., and the r.m.s. horse power 639. Curve 8 is for a test of the 28 by 36-in.

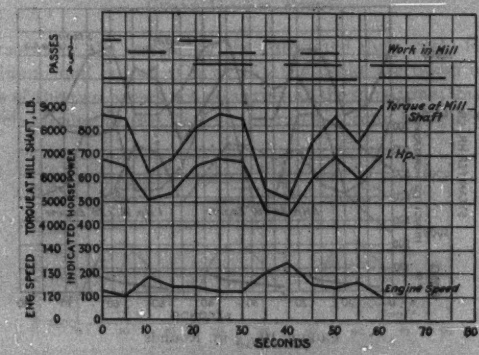
engine on this size. This test shows a maximum torque of 9300 lb. (4220 kg.), and a maximum h.p. of 740. Curve 9 gives the calculated duty cycle at the maximum mill output, the r.m.s.



CURVE 7—47/64-in. Rounds

torque being 8300 lb. (3760 kg.), the horse power 662, and the maximum horse power 780.

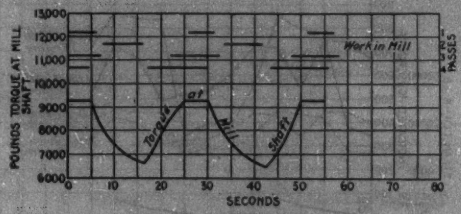
Curve 10 is for $\frac{7}{8}$-in. (22.2-mm.) round rods and shows that



CURVE 8—47/64-in. Rounds

the steam available is about equal to that required, but that a regenerator should be used. The maximum observed mill speed on this size was 382 rev. per min., and the average about 360 rev. per min., with a horse power of 510. Curve 11 is for

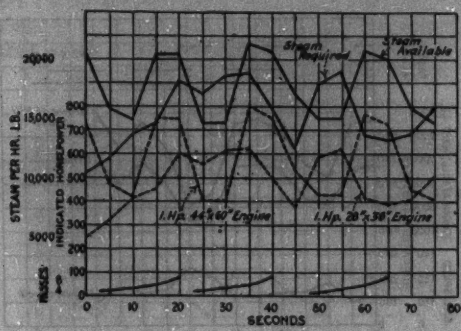
a test of the 28 by 36-in. engine on this size. The tests of this size show a maximum torque of nearly 10,000 lb. (4536 kg.) with about 650 horse power demand. Curve 12 gives the calculated duty cycle at the maximum mill output, the r.m.s.



CURVE 9—47/64-in. Rounds

torque being 8400 lb. (3810 kg.), the horse power 575, and the maximum horse power 650.

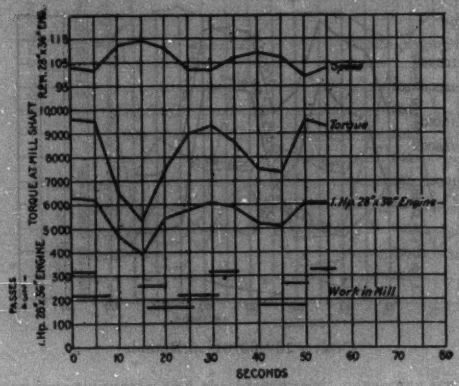
Curve 13 is for 63/64-in. (25-mm.) round rods and shows that the steam available exceeds the steam required. This is



CURVE 10—$\frac{1}{2}$-in. Rounds

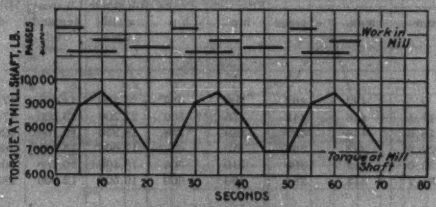
due to but two stands of finishing rolls being used. The maximum observed mill speed was 312 rev. per min., the average about 300 rev. per min., and the r.m.s. horse power 340. Curve 14 is for test No. 2, and Curve 15 for test No. 4 on this size. In test No. 2 both passes were in the mill at the same time,

resulting in very high peaks with long rest periods between, while in test No. 4 the two passes did not coincide. The total amount of work done, whether rolling is done with high peaks and long rest intervals, or low peaks and shorter rest periods,



CURVE 11—¾-in. Rounds

is practically the same. In the calculated duty cycle for the maximum mill output (Curve 16), the peaks are taken on the basis of the two passes not occurring at the same time; this gives a cycle similar to test No. 4, the r.m.s. torque being 6800 lb.

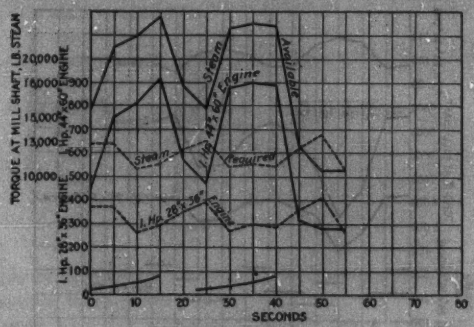


CURVE 12—¾-in. Rounds

(3080 kg.), the horse power 414, the maximum torque 9800 lb. (4445 kg.), and the horse power 545.

Curve 17 is for 1¼-in. (31.7 mm.) round rods and shows the steam required to be in excess of the steam available. The

maximum observed mill speed was 314 rev. per min., the average being 285 rev. per min., and the horse power about 400. Curve 18 is for a test of the 28 by 36-in. engine on this size, and shows high peaks when passes one and three coincide. Curve



CURVE 13—63/64-in. Rounds

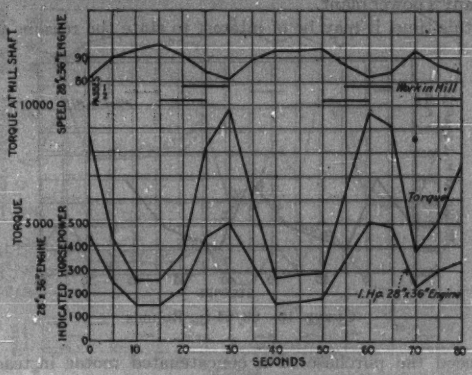
19 is the calculated torque to give maximum mill output and gives an effective torque of 7500 lb. (3400 kg.), with a horse power of 604, and a maximum horse power of 640.

A summary of the foregoing tests gives:

Diameter of Rod		Mill speed		Effective h.p.	Peaks h.p.	Lb. steam available	Lb. steam demanded	Mill speed desired
in.	mm.	max.	average					
3/8	9.5	472	462	500	669	25,300	14,900	475 – 480
29/64	11.5	456	442	425	509	21,200	13,500	475 – 480
47/64	18.6	448	432	639	738	18,250	19,100	420 – 435
7/8	22.2	382	360	510	635	17,600	15,300	360 – 375
63/64	25.0	312	300	340	506	18,400	10,250	305 – 310
1 1/4	31.7	314	285	400	600	10,500	13,000	285 – 300

The test results show that a large amount of exhaust steam would be lost if the low-pressure turbine were used for driving the finishing rolls direct. Also it was found that the low-pressure turbine would be wasteful of steam if the turbine speed varied with the mill speed. Gearing the turbine to the

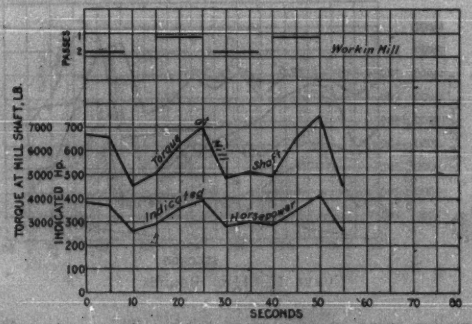
mill was not looked upon favorably, as the experience with several turbine gears on pump work had not been entirely satisfactory. Further objections to the turbine were the cost



CURVE 14—63/64-in. Rounds

of condensing water and the investment necessary for pumping equipment and pipe lines.

A careful consideration of the various drives resulted in the

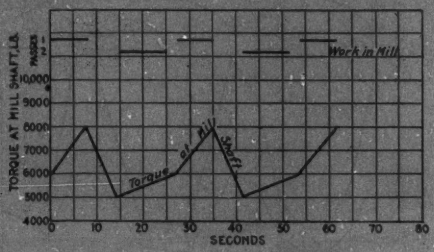


CURVE 15—63/64-in. Rounds

decision to install a motor drive, either a-c. or d-c., and obtain power from the steel company's central power plant. It was found that this would give an economical drive and be lower

in first cost than either a rope or geared engine. Also, the use of a motor would not interfere with the future installation of an exhaust steam turbine, which could operate in parallel with the company's power plant.

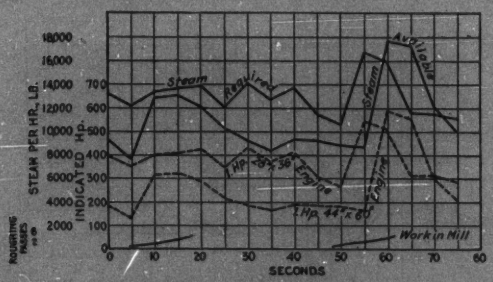
At this time, it may be of interest to state the reasons which



CURVE 16—63/64-in. Rounds

influenced the purchase of a concatenated motor instead of, first, a direct-current motor, or second, an induction motor operating with a speed-regulating set.

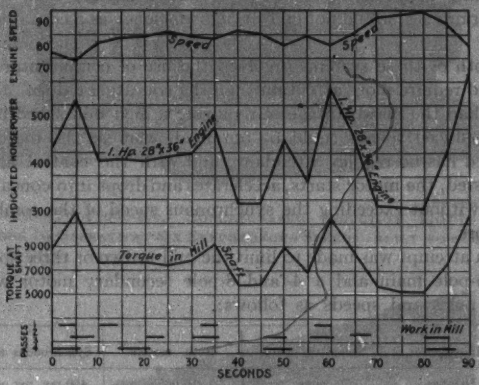
(1) The direct-current motor was entirely practical, but presented no advantages over the concatenated motor, except



CURVE 17—1¼-in. Rounds

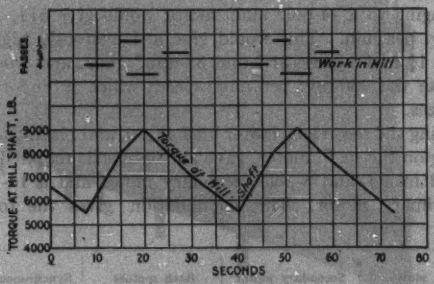
that smaller speed steps were possible. This was negligible because the concatenated set gave as many speeds as were necessary. The disadvantages of the direct-current motor were, that it was more expensive and, as it required a motor-generator set, less efficient.

(2) The speed-regulating set would have about the same or a slightly better efficiency than the concatenated motor, would be about the same in first cost and would have a higher power



CURVE 18—1½-in. Rounds

factor at low speeds. Its disadvantage lay in the fact that a commutator motor or synchronous converter would be required. Little was known about the performance of a commutator motor



CURVE 19—1½-in. Rounds

operating on the high frequency which would be obtained at this mill, commutator motors on mill work operating at frequencies around 20 cycles per second not being in satisfactory

service either here or abroad, and it is questionable if at the present time a guarantee for a satisfactory commutator motor could be obtained for the work of this mill.

Using a synchronous converter and a motor, or a motor-generator set, would not give as high efficiency as a concatenated set.

Both of these systems involved the use of commutators and would require more attention than the concatenated set. They also had the disadvantage of requiring a high mill speed before the reduced speeds could be obtained, whereas the motor installed has no regular attendant, and with the control as now adjusted, the motor starts, accelerates and drops into concatenation without exceeding the synchronous speed of the combined motors.

An attempt was made to limit the mill to two or three speeds. A 16-pole main and a 4- and 8-pole secondary motor would give poles and speeds as follows:

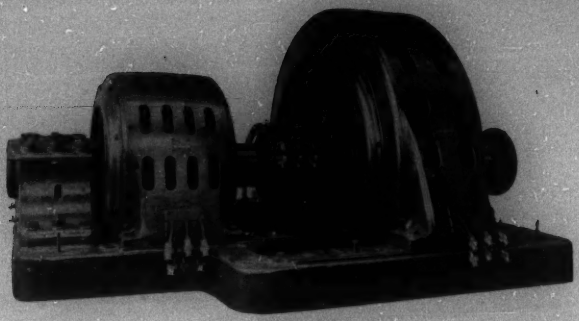
Main motor	Secondary motor	Both motors	Synchronous speed
16 poles	none	16 poles	450 rev. per min.
16 "	4 poles	20 "	360 "
16 "	8 "	24 "	300 "

This eliminated the 400-rev. per min. speed, which is one of the most important on the mill, about 40 per cent of the mill output being on this speed.

Changing to a 14-pole main motor would give 514, 400 and 327 rev. per min. This would give a dangerously high speed for the $1\frac{1}{4}$ and $1\frac{1}{2}$-in. (31.7 and 38-mm.) rods, and would also eliminate the 450-rev. per min. speed, which is important on some sizes.

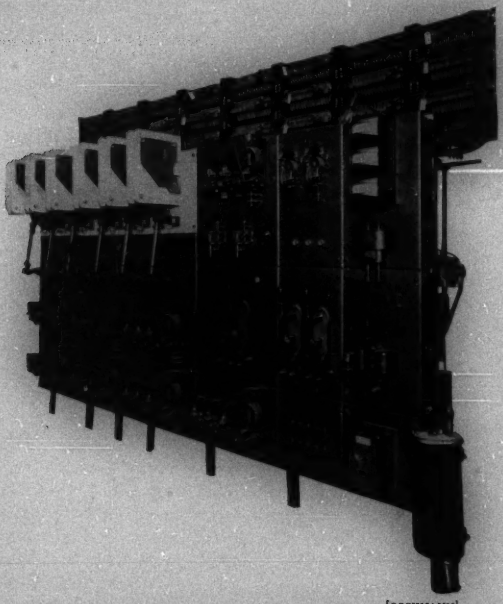
Leaving the secondary motor unchanged, and placing a double winding on the main motor, gave all the speeds required. This resulted in a 4- and 8-pole secondary motor and a 14- and 16-pole primary motor. This combination gives the following speeds:

Main motor.	Secondary motor	Both motors	Synchronous speed
14 poles	none	14 poles	514 rev. per min.
16 "	"	16 "	450 "
14 "	4 poles	18 "	400 "
16 "	4 "	20 "	360 "
14 "	8 "	22 "	327 "
16 "	8 "	24 "	300 "



[OSCHMANN]

FIG. 2—2200-VOLT 600-H.P. CONCATENATED INDUCTION MOTOR SET ARRANGED TO OPERATE AT SIX SYNCHRONOUS SPEEDS, BUILT FOR OLIVER IRON AND STEEL COMPANY.



[OSCHMANN]

FIG. 4—SWITCHBOARD FOR PRIMARY AND SECONDARY CONTROL CIRCUITS OF SIX-SPEED CONCATENATED INDUCTION MOTOR.

All these speeds are obtained by direct concatenation; theoretically, speeds corresponding to 6, 8, 10 and 12 poles can also be obtained by differential concatenation.

It was decided to install this motor, the motor to consist of a double-wound main motor and single-wound secondary motor, the first or primary motor to be 14 and 16 poles and have a wound rotor, the second or secondary motor to have its winding arranged for 4- and 8-pole connection, its rotor to be of the squirrel cage type. Both stators were mounted on a common bed-plate and the rotors on a common shaft, resulting in the motor shown in Fig. 2.

The larger motor receives three-phase energy at 2200 volts, 60 cycles, on either a 14- or 16-pole stator winding. Both 14- and 16-pole windings lie in the same stator slots and have the same coil pitch and coil size. The coil connections of the 14-pole windings are brought out on one side of the frame, the coil connections for the 16-pole winding being on the opposite side, thus making the connections of either winding readily accessible. The windings on the rotor of this motor are similarly arranged. The six leads from the rotor windings are connected to six split bronze collector rings mounted on the shaft between the two motors. These rings can be easily renewed.

The small motor has a single stator winding which can be connected in either four- or eight-pole combination; the pole changing is accomplished by means of oil switches located on the motor control board. The rotor of this motor is of the squirrel-cage type and has electrically welded bars and end rings. The rotor bars are of sufficient cross-section to resist the action of centrifugal force and will not bend out and damage the stator winding, should they become detached from the end rings.

The floor space taken by the complete unit is 14 ft. 8 in. by 10 ft. 7 in. (4.47 by 3.22 m.), and the greatest height above the floor is 6 ft. 10 in. (2.08 m.). The rotors are 5 ft. 9 in. (1.75 m.) and 2 ft. 10 in. (86 cm.) in diameter respectively, mounted on a shaft 14 in. (35.6 cm.) in diameter. The general construction of the motor is heavy. The rotor spiders are of cast steel and the motor is built to stand reversing at full speed. The two bearings, each 8 by 20 in. (203 by 508 mm.), are self-aligning and of the ring-oiled type. The motor and mill are connected by a flexible coupling, the bearing next the mill and the coupling hub forming a thrust bearing. The brush holders for the col-

lector ring brushes can be removed and either stator slipped aside to give access to any part of the stator or rotor windings.

The motor was installed about where the mill pulley formerly was, the present mill plan being shown in Fig. 3.

For the operation of the motor no regular attendant is needed, as the changing of speeds is simple and requires no electrical knowledge or experience. The engineer on the 44 by 60-in. (112 by 152-cm.) engine attends to all speed changes and also

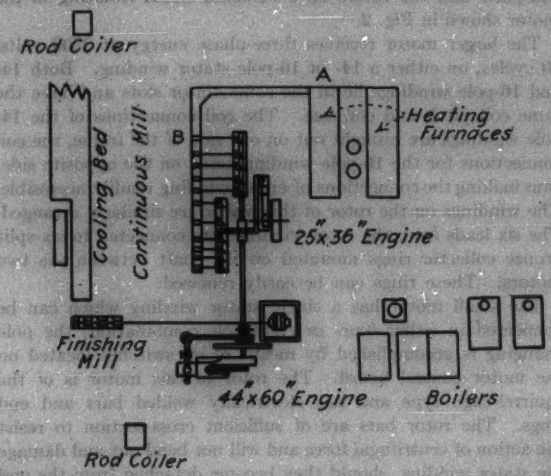


FIG. 3

starts and stops the motor. The controller for the motor is mounted adjacent to the throttle of the engine. In practise it has been found that, having the motor controller near the engine throttle, the engineer can handle both mills easily, the extra work and attention required being almost negligible.

The ease and simplicity in handling the mill is one of the best points in favor of the concatenated motor, as has been shown repeatedly in stopping the mill and backing out "stickers", or pieces caught in guides and refusing to go through rolls. The motor can be stopped, reversed and the sticking rod backed

out, the motor again stopped, restarted and immediately accelerated to full operating speed. This is generally done in time to roll the billets coming through the continuous mill and prevent their being scrapped. On several occasions this has taken place, the quick stop and start saving about a third of a ton of steel from becoming scrap. The total time of stopping, backing out, stopping and accelerating to operating speed, was less than a minute. The stopping and reversing was easily done, and no apparent strain or distress on motor or control was noticeable.

The control board for this motor is shown in Fig. 4. The wiring diagram is shown in Fig. 5. The choke coils, lightning arresters and disconnecting switches are mounted on the wall of the motor house and are connected to the control board through series transformers for wattmeter and overload relays to switch *A*. These transformers are connected in Z and give overload protection on all three phases.

Oil switch *A* is a triple-pole circuit breaker, having inverse-time-limit overload trip and low-voltage release, and is also provided with a magnetically operated lockout which prevents switch *A* from being closed unless both main line contactors *F* and *R* are open. This is provided to prevent the mill from starting should the engineer attempt to close switch *A* and not notice that the main line contactors had remained closed.

From switch *A*, current passes to the forward and reverse main line contactors *F* and *R*, one phase passing through a series transformer which operates the current-limit relays *CR* which control the resistance contactors.

F and *R* are three-pole, 2200-volt, magnetically operated air-break contactors. A mechanical and electrical interlock is provided between these contactors. The electrical interlock is not the conventional interlock disks working on the connections of the magnet coils, but consists of a small shunt transformer *TL* with its primary connected across one phase of the contactors as shown (Fig. 5). The secondary of the transformer operates the small contactor *L*. Contactors *F* and *R* have their operating circuit closed through contactor *L* or the interlock on *L*. As long as there is potential on the motor, contactor *L* will remain closed and thereby prevent either *F* or *R* from closing. As soon as *L* opens, either *F* or *R* can close, depending on the position of the master controller. This method of interlocking was deemed necessary, as the operation of the contactors is so

rapid that in reversing the motor, one contactor might close before the arc on the other was ruptured, and thereby produce a short circuit through the arc on the open contactor. The present arrangement has proved entirely satisfactory.

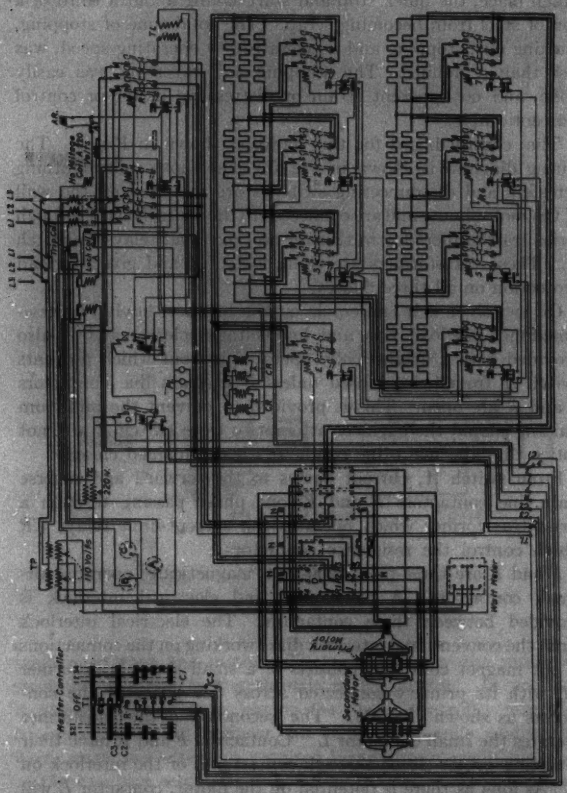


FIG. 5

The operation of the main line contactors shows that double-pole contactors would be as satisfactory as the triple-pole contactors installed. As the arcs, particularly the heavy arcs,

are always single-phase, switch *B* might also be double-pole instead of triple-pole.

From contactor *F* and *R*, current passes to oil switch *B*, where connection is made to either the 14- or 16-pole stator winding of the primary motor. Oil switch *B* is mechanically connected to oil switch *C*, so that *B* and *C* are operated by one handle. Switch *C* controls the rotor winding of the primary motor. Closing switch *B* on the 14-pole side will also close switch *C* on its 14-pole side. From switch *C* the current passes to a grid resistance mounted above the control board. This resistance is ample to reduce the mill speed to about 50 rev. per min. and hold it at this point for 15 to 20 minutes, the friction of the mill being the only load. This low speed is used to adjust the rolls and roll trial bars. The end of the resistance is either short-circuited by contactor *E* or the current passes into switch *D*, where it is directed into the stator of the secondary motor. Switch *D* is mechanically connected to switch *M*. These switches give either the 4- or 8-pole connection on the stator of the second motor. Closing switch *D* on the 1, 2 and 3 side gives a single-circuit eight-pole delta connection to the stator of the secondary motor; closing *D* on the 4, 5 and 6 side also closes switch *M* and gives a double-circuit four-pole star connection to the stator of the secondary motor. Switch *D* is provided with interlock switches *I* and connected to contactor *E* and arranged to close contactor *E* when switch *D* is open. To avoid having the mill try to accelerate from a concatenated to a direct speed should switch *D* open and thereby close contactor *E*, switch *D* is provided with a lock *N*, so that it cannot be opened or closed unless the master controller is placed on the off point and switch *A* is open. Switches *V* and *C* are provided with similar locks. The pilot lights *PL* indicate the position of the master controller; their circuit is closed when the controller is on the starting or running points. Current for the pilot lamps and small solenoids *N* which operate the locks on switches *A*, *B*, *C* and *D* is obtained from the potential transformers *TP*, and is independent of the position of switch *A*.

Contactors 1 to 7 are triple-pole low-voltage contactors and are arranged to short-circuit portions of the resistance; they are connected so that a contactor sticking or remaining closed will not produce dangerous currents in starting or reversing. These contactors are controlled by current from transformer *TC*, which is connected to the control side of switch *A*; current from the transformer passes through contactor *O* to current limit relays,

CR, which are set to close the contactors in regular sequence when the starting current drops to about full-load value. When operating on the 14- or 16-pole speeds, contactors 6 and 7 will remain open and give a 10 per cent slip at full load; by closing switch *R6*, contactor 6 will close and give a 5 per cent slip at full speed. Contactor 7 is always open on the 14- or 16-pole speed.

When operating on the concatenated speeds, contactor *E* is open and interlocks on *E* are closed, which allows contactors 6 and 7 to close, current limit the same as the remaining contactors, thereby leaving the motor without external resistance in the rotor circuit other than the resistance of the wires. Contactor *O* controls the current for all contactors except itself and contactor *L*. Contactor *O* is used to prevent the motor from starting upon the resumption of power in case of the failure of switch *A* to open should the power supply be interrupted. Contactor *O* opens on failure of power and can only be closed by placing the master controller in the off position.

The master controller is located about 80 ft. (24 m.) distant from the control board, and to guard against the master controller becoming inoperative, switch *CS*, located near the master controller, is provided. The action of switch *CS* is to open all the contactors and oil switch *A* and stop the motor should the master controller be out of order.

A test switch *AT* is provided on the control board which opens oil switch *A*. Resistance *AR* is connected across switch *AT* so that when switch *AT* is open, a slight current passes through the low-voltage release coil of switch *A*. This current is just sufficient to neutralize whatever residual magnetism may remain in the armature of the low-voltage release, and causes it to drop at once and open switch *A*.

It will be noted that the starting resistance is connected between the rotor of the main and the stator of the secondary motor. The circuit between the motors is established before the motors are started and the entire starting current passes through the secondary motor. This simplifies the control of the mill and makes the starting simple, as this method allows the mill to come directly to whatever speed the control is set for.

In stopping the mill, the master controller is usually placed in the off position, and the motor allowed to stop gradually. In emergency the motor can be reversed at full speed; in reversing on the concatenated speeds the secondary motor acts as a part of the circuit. The simplicity of this method is obvious.

The operation of this control is as follows:

Disconnecting switches are closed and power is on the lines. Master controller is on off point and oil switch *A* is open.

For Direct Speeds

Close switch *B* for either 14 or 16 poles. Close switch *A*. Closing switch *A* closes contactor *E* through interlock *L* on switch *D*. Contactor *O* also closes, its circuit being closed through segment *C* on master controller. After closing, *O* will remain closed regardless of position of the master controller, its holding circuit being established by the interlocks on *O*.

Starting. Placing the master controller on the first point closes either *F* or *R*; this puts potential on the main motor and closes contactor *L*. Placing the controller on the second point, contactor No. 1 can close. Placing the controller on the third point, contactor No. 2 can close. Placing the controller on the fourth point, contactor Nos. 3, 4, 5 can close. Contactor 6 can close if switch *R6* is closed; contactor 7 cannot close as its closing circuit is open at contactor *E*. Under operating conditions the master controller is placed directly on the fourth or running point, and the contactors close in regular sequence at about full-load current, their control being the usual current limit type for a-c. contactors.

Reversing. When master controller is thrown from forward to reverse, contactor *R* will close as soon as arc on *F* is interrupted, and thereby open contactor *L*.

Concatenated Speeds

Oil switch *B* is placed on either the 14- or 16-pole connection. Switch *D* is closed for either 4- or 8-pole connection. Oil switch *A* is closed, when contactor *O* closes as before. Contactor *E* does not close, however, as its closing circuit is open at interlock *I* on switch *D*.

Starting, Running and Reversing. Exactly the same as for direct speeds, except that contactors 6 and 7 will close current limit the same as the rest of resistance contactors.

Summary

The control as used on this motor is more simple than a speed-regulating control in its operation, and is comparable with the magnetic control of a single-speed motor. The starting, stopping and reversing are as easily accomplished as if the motor were a single-speed motor. The only difference in handling is to operate switches *B* and *D* to secure the proper pole connection, and as this is generally done while changing rolls, it causes no delay or inconvenience. The only serious objection to the con-

catenated set is the low power factor on the concatenated speeds. The low power factor in this particular case has not been found serious. The power plant has a larger day than night load, so that the concatenated set working on the day shift reduces the power factor at the power plant but slightly. The lowest speeds, and therefore the lowest power factor, are generally obtained on the night shift. However, several synchronous motors (installed about five years ago), operate at reduced loads on the night shifts and it has been found that about 100 per cent power factor can be readily obtained at the power plant during the night, and 87 to 90 per cent during the day.

The criticism has been made that the control of concatenated motors is complicated: in reply to this, I would state that this motor has six definite speeds and two additional resistance speeds. Switches and contactors are provided to take care of these speeds and in addition the control has been further complicated in order to make the operation of the motor and control as fool-proof as possible, and thereby make unnecessary a special attendant at the mill.

The motor was installed in June, 1913; up to this time (April 1914) there have been only three mill interruptions, all of which were due to the control apparatus, as follows:

(1) An open circuit at interlock on contactor *F* which allowed low-voltage release to drop and open switch *A*. This interlock consists of a ½-in. (12.7-mm.) copper rod pressing against a copper block contact; the copper rod is insulated and clamped to the contactor. The clamp became loose and allowed the rod to slip out and open the circuit.

(2) Defective low-voltage release coil on switch *A*.

(3) Burnt-out potential coil on one of the current-limit relays *CR*.

The total time lost due to these three interruptions was 68 minutes, and it will be noted that, excepting the first, not one of these interruptions was due to the design or type of the control, but rather to minor defects in manufacture. The motor has easily performed the work demanded of it, and the results obtained have justified the choice of this type of motor drive.

Should the same problem be presented for solution at this time, it would probably be solved in the same manner, notwithstanding the recent advances made in speed-regulating systems. It should also be noted that the ease of handling this motor and the ability to do without a trained operator make this type of motor extremely desirable.

DISCUSSION ON "CONCATENATED INDUCTION MOTORS FOR ROLLING MILL DRIVE" (OSCHMANN), DETROIT, MICH., JUNE 23, 1914.

Rudolph Tschentscher: The three points which stand out very prominently to me as a steel man are these: First, the exceptional reliability of the equipment—it entailed a loss of a little over one hour's time in practically a year's operation; second, the low operating cost, there being no additional attendance required; and third, probably greater than either of the other two, the rapidity of the control movement. I think the paper gives the time for braking, and reversing the forward motion, as being done within one minute. That, to one in the steel business, means a very considerable saving in tonnage.

T. E. Tynes: One of the experiences that probably all steel mill men have had, is that when you ask the management to put in new equipment, they come back to you with the argument "The first thing you will want is a spare unit to take care of that in case there is a breakdown." I am glad to note the reliability of this set Mr. Oschmann has just described. Probably it does not need a spare unit. I see no reason why, in the modern mill motor and the modern equipment the manufacturers are giving us, we cannot say we have as reliable apparatus as the steam engine.

A. E. Averrett: I would like to mention one feature in concatenated motors. In case of a small reduction in speed, such as 14 or 16 poles concatenated with 4 poles, the efficiency and power factor will remain quite high, but when a speed reduction to ½ or thereabouts takes place the power factor is very much reduced due to the second motor drawing its current through the first motor; the output of both motors being approximately equal. With rheostatic control the power factor would remain high, but the efficiency would go down proportionally to the speed; with concatenated control the reverse takes place, that is, high efficiency, but power factor reduced approximately proportionally to speed. Therefore, large speed reduction by concatenation is at the expense of power factor.

Presented at the 31st Annual Convention of the American Institute of Electrical Engineers, Detroit, Mich. June 24, 1914, under the auspices of the Electrophysics Committee.

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THE SPHERE GAP AS A MEANS OF MEASURING HIGH VOLTAGE

BY F. W. PEEK, JR.

ABSTRACT OF PAPER

A gap method of measuring high voltage is desirable in certain tests because a gap measures the maximum point of the voltage wave.

The needle gap is unreliable, and is subject to large corrections due to humidity, etc. The sphere gap is free from complicated corrections and the curve is subject to calculation. Wherever voltage is measured by a gap, correction must be made for air density—that is, altitude or barometric pressure, and temperature. The laws for this correction have been deduced for the sphere gap, from tests, over an air density range equivalent to that from sea level to 18,000 ft. elevation. An equation is given for calculating sphere spark-over curves for various spacings, radii, air density, etc.

Standard measured curves for convenient sizes of spheres at sea level are given for practical use, as well as a table for applying these curves to any altitude. The altitude correction may be made very accurately to the standard curve, either by applying the calculated correction constant or by applying the correction factor given in the tables.

The complete standard curves should not be calculated when reliable measured curves are available.

The effects of high frequency and impulse voltages are discussed. In making measurements certain precautions are necessary for accuracy, as well as for protection of apparatus. These precautions are discussed and test results are given.

A GAP method of measuring high voltages is often desirable in certain commercial and experimental tests. As a gap measures the maximum point of the voltage wave it is therefore used in many insulation tests where breakdown also depends upon the maximum voltage point. In most commercial tests an accuracy of one or two per cent is sufficient. A greater accuracy can be obtained with the sphere gap for special work where proper precautions are taken.

THE NEEDLE GAP

The needle gap is unreliable at high voltages because, due to the brush discharge and broken-down air that precedes the spark-over, variations are caused by humidity, oscillations, and frequency.[1]

The needle gap is also inconvenient because needles must be

1. Discussion, F. W. Peek, Jr., TRANS. A. I. E. E., Vol. XXXII, 1913, p. 812. *G. E. Review*, May, 1913.

replaced after each discharge; the gap becomes very long at high voltages, and the calibration varies somewhat with the sharpness of the needle.

The effect of humidity is shown in Fig. 1, where it can be seen that a higher voltage is required to spark over a needle gap when the humidity is high than when it is low. (Curves of Fig. 1 are intended only to illustrate this effect and not for use in making accurate measurements). It is probable that the corona streamers in humid air cause a "fog", and then agglomerate the water particles, which, in effect, increase the size of the electrodes.

All spark curves of whatever form of gap must be corrected for air density; that is, altitude and temperature. For *low voltages* the spark-over voltage of the needle gap decreases approximately as the air density. At higher voltages the effect becomes erratic, probably due to humidity.

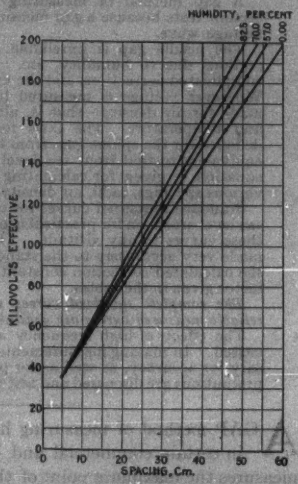

FIG. 1—APPROXIMATE NEEDLE GAP CURVES FOR DIFFERENT RELATIVE HUMIDITIES

THE SPHERE GAP

The voltage required to spark over a given gap between spheres increases with the diameter of the sphere. Corona cannot form on spheres, or rather, the spark-over point and corona point are coincident if the spacing is not greater than the diameter of the sphere. Practically a spacing as great as three times the radius may be used without appreciable corona. The voltage limit of a given sphere in high-voltage measurements is thus reached when a gap setting greater than three times the radius is required. A larger sphere should then be used.* With this space limit, the first evidence of stress is complete spark-over; corona can never form, and all of the undesirable effects and variables due to brush

*More accurate and consistent results are obtained, however, for spacings less than 2 *R*.

discharge and broken-down air are eliminated. Humidity has no appreciable effect.

The space factor is relatively small. Several thousand measurements may be made without repolishing. The curve may be calculated. The only correction is the air density correction. This has been investigated and the results are given below. The correction is quite simple. Fig. 2 gives typical sphere-gap curves for both spheres insulated and for one sphere grounded. Tables I to V give spark-over curves for 6.25-, 12.5-, 25-, 50- and 100-cm. spheres at sea level (25 deg. cent., 76 cm. barometer). $\delta = 1$. (See Note 2).

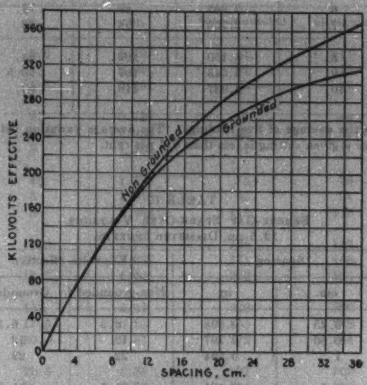

FIG. 2—SPARK-OVER CURVES
25 cm. diam. spheres

Calculation of Curves: The gradient or stress on the air at the sphere surface, where it is greatest, is found mathematically:

$$g = \frac{e}{x} f \text{ kv. per cm.}$$

where e is the applied voltage in kilovolts, x is the spacing in centimeters, f is a function of $\frac{x}{R}$, and R is the radius of the sphere in centimeters.

2. *The Calibration of the Sphere-Gap Voltmeter*, Chubb and Fortescue, TRANS. A.I.E.E., Vol. XXXII, 1913, p. 739. Discussion by F.W. Peek, Jr., p. 812. "The Sphere Gap as a Means of Measuring High Voltage," F. W. Peek, Jr., *G. E. Review*, May, 1913.

TABLE I

SPHERE-GAP SPARK-OVER VOLTAGES
6.25-cm. DIAMETER SPHERES.

Spacing		Kilovolts effective	
cm.	in.	Non-grounded	Grounded
0.5	0.197	12	12
1.	0.394	22.5	22.5
1.5	0.591	31.5	31.5
2	0.787	41.	41.
3	1.181	57.5	56.
4	1.575	70.5	66.
5	1.969	81.	73.
6	2.362	89.	79.
7	2.756	96.	83.
8	3.150	102.	88.
9	3.543	107.	90.5
10	3.937	110	93.

Each point is the average of five readings. The average variation between maximum and minimum for a given setting is less than 0.5 per cent.

TABLE II

SPHERE-GAP SPARK-OVER VOLTAGES.
12.5-cm. DIAMETER SPHERES.

Spacing		Kilovolts effective	
cm.	in.	Non-grounded	Grounded
0.25	0.098	6.5	6.5
0.50	0.197	12.	12.
1	0.394	22	22.
1.5	0.591	31.5	31.5
2	0.787	41	41.
3	1.181	59	59.
4	1.575	76	75
5	1.969	91	89
6	2.362	105.	102
7	2.756	118.	112
8	3.150	130	120
9	3.543	141.	128
10	3.937	151.	135
12	4.72	167.	147
15	5.91	188	160
17.5	6.88	201	168.
20.	7.87	213.	174.

Then $$g_s = \frac{e_s}{x} f \text{ kv. per cm.}$$

where e_s is the spark-over voltage and g_s is the apparent strength of air.

f is found mathematically and tabulated in Table VI[3] for the non-grounded and grounded cases. For the non-grounded* case it

TABLE III

SPHERE-GAP SPARK-OVER VOLTAGES.

25-cm. DIAMETER SPHERES

Spacing		Kilovolts effective	
cm.	in.	Non-grounded	Grounded
0.5	0.197	11	11
1.	0.394	22	22
1.5	0.591	32	32
2.	0.787	42	42
2.5	0.983	52	52
3	1.181	61	61
4.	1.575	78	78
5	1.919	96	94
6	2.362	112	110
7.5	2.953	135	132
10.	3.937	171	166
12.5	4.92	203	196
15.	5.91	230	220
17.5	6.88	255	238
20.	7.87	278	254
22.5	8.85	297	268
25.	9.83	314	280
30.	11.81	339	300
40.	15.75	385	325

was found experimentally that g_s, the apparent surface gradient at spark-over, increased with decreasing radius of sphere, as g_s for corona on wires increases for decreasing radius of wire. For a given size of sphere, g_s is practically constant, independent of spacing, between the limits of $x = 0.54\sqrt{R}$ and $x = 2R$.

3. See *Law of Corona III*, F. W. Peek, Jr., TRANS. A. I. E. E., Vol. XXXII, 1913, p. 1767. G. R. Dean, *G. E. Review*, March, 1913; *Physical Review*, Dec. 1912 and April 1913. Russel—*Philosophical*, May 1906.

*Non-grounded here means with neutral at the mid point. It is thus, in this case, preferable to ground the transformer neutral.

The *average* gradient between these limits of separation is[4]

$$g_s = 27.2 \left(1 + \frac{0.54}{\sqrt{R}}\right) \text{ kv. per cm. max.} \qquad (1a)$$

$$g_s = 19.3 \left(1 + \frac{0.54}{\sqrt{R}}\right) \text{ kv. per cm. eff. sine wave.} \qquad (1b)$$

TABLE IV
SPHERE-GAP SPARK-OVER VOLTAGES.
50-cm. DIAMETER SPHERES

Spacing		Kilovolts effective	
cm.	in.	Non-grounded	Grounded
		*	
2	0.787	40	40
4	1.575	76.5	76
6	2.362	115.5	112
8	3.150	149	145
10	3.937	189	185
12	4.72	224.3	220
14	5.51	255.5	250
16	6.30	285	275
20	7.87	335	320
25	9.83	393	377†
30	11.81	445	420
35	13.80	493	456
40	15.75	537	489
45	17.72	573	516
50	19.19	605	541
55	21.65	633	561
60	23.62	660	579
65	25.60	684	594
70	27.56	705	608
75	29.55	725	619

*These values are calculated.
†Spacings above 22 cm. are calculated.

The maximum variation from the average between the limits may be 2 per cent. When x is less than $0.54\sqrt{R}$, g_s increases very rapidly because the spacing is then less than the "rupturing energy distance."[5] Above $x = 3\ R$, g_s apparently gradually increases[5]. This increase seems only apparent and due to the

4. See *Law of Corona III*, F. W. Peek, Jr., TRANS. A. I. E. E., Vol. XXXII, 1913, p. 1767.
5. Ibid.

shanks, surrounding objects, etc., better distributing the flux or lessening the flux density. When *both spheres are insulated* and of practical size, the change is not great within the prescribed limits. When *one sphere is grounded*, however, this apparent increase of gradient is very great if the mathematical f, which does not take account of the effect of surrounding objects, is used. For this reason this f_0 was determined experimentally, for the grounded case, by assuming g_s constant within the limits,

TABLE V

SPHERE-GAP SPARK-OVER VOLTAGES.
100-cm. DIAMETER SPHERE.

Spacing		Kilovolts effective	
cm.	in.	Non-grounded	Grounded
1.0	0.394	20	20
3.0	1.181	60	60
5.0	1.969	100	100
10.0	3.937	195	195
15.0	5.91	283	280
20.0	7.87	364	360
30.0	11.81	520	505
40.0	15.75	650	615
50.0	19.69	770	730
60.0	23.62	870	810
70.0	27.56	956	895
80.0	31.50	1044	956
90.0	35.43*	1107	1010
100.0	39.37	1182	1057
110.0	43.35	1238	1090
120.0	47.20	1290	1133
130.0	51.20	1335	1160
140.0	55.70	1378	1189
150.0	59.10	1412	1212

These values are calculated.

as it is in the non-grounded case, and finding values of f_0 corresponding to the different values of $\frac{x}{R}$. These measurements were made with the grounded sphere 4 to 5 diameters above ground. Any given value of the ratio $\frac{x}{R}$ should require a constant f_0 to keep g_s constant independent of R. This was found to check.

The curves may be quite closely calculated thus:

$$e_s = g_s \frac{x}{f} \text{ (non-grounded) effective sine wave.} \qquad (2)$$

$$e_s = g_s \frac{x}{f_0} \quad \text{(grounded) effective sine wave} \tag{3}$$

where g_s is calculated from equation (1b), and f_0 or f is found from the table for the given $\frac{x}{R}$. *Curves need be calculated only when standard measured curves cannot be obtained.* Measured curves are given here. The average error, however, for curves calculated from the above equations, for 2-cm. diameter spheres and over, should not be greater than 2 or 3 per cent. The accuracy of calculations is not as great as in the case of the starting point of corona on wires.

TABLE VI

SPHERE-GAP GRADIENT FACTOR.

$\frac{X}{R}$	Non-grounded. Mathematical and actual practical coefficient* f	One sphere grounded. Actual practical coefficient f_0	One sphere grounded. Mathematical coefficient not correct on account of effect of shanks, etc. f_1
0.1	1.034	1.034	1.050
0.3	1.103	1.105	1.162
0.5	1.175	1.180	1.280
1.0	1.366	1.410	1.620
1.5	1.568	1.675	2.000
2.0	1.781	1.965	2.415
2.5	2.002	2.27	2.85
3.0	2.225	2.59	3.30
3.5	2.455	2.90	3.76
4.0	2.686	3.20	4.23

*Non-grounded: $f = \frac{1}{4}\left(\frac{X}{R} + 1 + \sqrt{\left(\frac{X}{R} + 1\right)^2 + 8}\right)$

One sphere grounded: $\begin{cases} f_0 = \text{experimental values.} \\ f_1 = \frac{1}{2}\left(\frac{X}{R} + \sqrt{\left(\frac{X}{R}\right)^2 + 4}\right) \end{cases}$

f_1 should not be used—see note above. f_0 should be used for the grounded case. The experimental values were determined with the grounded sphere four to five diameters above ground.

Effect of Air Density or Altitude and Temperature

We have found that the average gradient for various air densities may be expressed

$$g_s = 27.2\,\delta\left(1 + \frac{0.54}{\sqrt{\delta R}}\right) \text{ kv. per cm. max.}$$

$$g_e = 19.3\,\delta\left(1 + \frac{0.54}{\sqrt{\delta R}}\right) \text{ kv. per cm. effective}$$

where δ is the relative air density

$$\delta = \frac{3.92\,b}{273+t}$$

b = barometric pressure in cm.
t = temperature in deg. cent.

The standard sea-level curves correspond to 76 cm. barometric pressure and 25 deg. cent. or where $\delta = 1$.

Correction Factor. The standard curve may be made to apply to any given altitude by multiplying the voltage at different spacings by the correction factor, thus:

$$e_1 = e\left[\frac{19.3\,\delta\left(1 + \frac{0.54}{\sqrt{\delta R}}\right)}{19.3\left(1 + \frac{0.54}{\sqrt{R}}\right)}\right] \tag{4}$$

$$= e\,\delta\,\frac{\left(1 + \frac{0.54}{\sqrt{\delta R}}\right)}{\left(1 + \frac{0.54}{\sqrt{R}}\right)} = e\,k$$

Practical Application. In order to avoid the trouble of calculating in practise, the factor is tabulated in Tables VII and VIII. This correction is very accurate. Table VII gives the correction factor for different sizes of spheres at different barometric pressures and at constant temperature. When volt-

TABLE VII

Approximate corresponding altitude ft.	Barometer		Values of k at 25 deg. cent. for standard spheres of the following diameters. Centimeters.						
	cm. Hg	in. Hg	6.25	12.5	25	37.5	50	75	100
0	76.00	29.92	1.000	1.000	1.000	1.000	1.000	1.000	1.000
500	74.58	29.36	0.981	0.980	0.980	0.979	0.979	0.979	0.979
1,000	73.14	28.79	0.964	0.963	0.962	0.961	0.960	0.960	0.960
1,500	71.77	28.25	0.948	0.946	0.945	0.944	0.943	0.942	0.942
2,000	70.42	27.72	0.932	0.929	0.927	0.926	0.925	0.924	0.924
2,500	69.09	27.20	0.916	0.913	0.911	0.909	0.908	0.907	0.907
3,000	67.74	26.67	0.902	0.899	0.897	0.895	0.893	0.892	0.891
3,500	66.51	26.18	0.887	0.884	0.882	0.880	0.878	0.876	0.875
4,000	65.25	25.69	0.873	0.870	0.867	0.865	0.863	0.861	0.860
4,500	64.01	25.23	0.859	0.855	0.852	0.850	0.848	0.846	0.845
5,000	62.79	24.72	0.845	0.841	0.838	0.835	0.833	0.831	0.830
6,000	60.45	23.80	0.817	0.812	0.808	0.805	0.803	0.801	0.800
7,000	58.22	22.93	0.791	0.786	0.782	0.779	0.776	0.774	0.772
8,000	56.03	22.05	0.765	0.759	0.754	0.750	0.748	0.746	0.744
9,000	53.84	21.20	0.739	0.733	0.728	0.724	0.721	0.719	0.717
10,000	51.85	20.41	0.716	0.709	0.703	0.698	0.694	0.692	0.690
12,000	48.09	18.93	0.669	0.661	0.656	0.651	0.647	0.644	0.642
15,000	42.88	16.88	0.606	0.596	0.589	0.585	0.580	0.577	0.575

age strikes across a given gap, its value, e_1, may be found by taking the voltage e, corresponding to the gap, from the standard curve and multiplying by the correction factor k, or a curve may be plotted corresponding to a given barometric pressure, thus

$$e_1 = ek.$$

TABLE VIII

Calculated values of k for different values of δ

$$k = \delta \left\{ \frac{1 + \dfrac{0.54}{\sqrt{\delta R}}}{1 + \dfrac{0.54}{\sqrt{R}}} \right\}$$

$$= \sqrt{\delta}\, \frac{\sqrt{\delta R} + 0.54}{\sqrt{R} + 0.54}$$

Relative air density	Values of k. Diameter of standard spheres in cm.						
δ	6.25	12.5	25.	37.5	50.	75.	100.
0.50	0.547	0.535	0.527	0.522	0.519	0.519	0.518
0.55	0.594	0.583	0.575	0.570	0.567	0.565	0.564
0.60	0.640	0.630	0.623	0.618	0.615	0.613	0.612
0.65	0.686	0.677	0.670	0.665	0.663	0.661	0.660
0.70	0.732	0.724	0.718	0.714	0.711	0.709	0.708
0.75	0.777	0.771	0.766	0.762	0.759	0.757	0.756
0.80	0.821	0.816	0.812	0.809	0.807	0.805	0.804
0.85	0.866	0.862	0.859	0.857	0.855	0.854	0.853
0.90	0.910	0.908	0.906	0.905	0.904	0.903	0.902
0.95	0.956	0.955	0.954	0.953	0.952	0.951	0.951
1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.05	1.044	1.045	1.046	1.047	1.048	1.049	1.049
1.10	1.090	1.092	1.094	1.095	1.096	1.097	1.098

Table VIII gives the correction factor for various values of δ. The value of δ may be calculated for the given temperature and barometric pressure, and a correction factor then found from the table. Fig. 3 gives the standard curve for the 12.5-cm. sphere (non-grounded, 25 deg. cent., 76 cm. bar. pressure) and curves calculated therefrom for 25 deg. cent. and various barometric pressures.

Experimental Determination of Air Density Correction

Tests. The equation (4) for the air density correction factor was determined by an extensive investigation of the spark-over of spheres in a large wooden cask arranged for exhaustion of air. This cask was built of paraffined wood and was 2.1 meters high by 1.8 meters inside diameter.

Tests were made by setting a given size of sphere at a given spacing, gradually exhausting the cask, and reading spark-over voltage at intervals as the air pressure was changed. (Temperature was always read, but varied only between 16 deg. and 21 deg. cent). This was repeated for various spacings on spheres ranging in diameter from 2.0 cm. to 25 cm. At the start, the

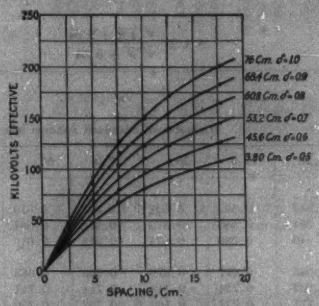

Fig. 3—Sphere Gap Spark-Over Voltage at Various Air Pressures

Temperature 25 deg.cent. 12.5-cm. spheres. Non-grounded. Drawn curves calculated. 76 cm. is standard curve. Points are from curves through measured values.

possible effect of spark-overs on the succeeding ones in the cask was investigated and found to be nil or negligible. A resistance of one to four ohms per volt was used in series with the spheres. Wave shape was measured and corrected for. Voltage was read on a voltmeter coil, by step-down transformer, and by ratio. Precautions were taken as noted in the discussion referred to below.[6]

In order to illustrate the method of recording data, etc., a small part of the data for various spheres and spacings is given in Tables IX to XVIII. Numerous data are plotted in curves,

6. *The Calibration of the Sphere-Gap Voltmeter*, Trans. A.I.E.E., Vol. XXXII, 1913, p. 739. Discussion by F. W. Peek, Jr., p. 812.

TABLE IX

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS

2.54-cm. DIAMETER SPHERES—NON-GROUNDED.

Spacing cm.	Spacing in.	Temp deg. cent.	Press. in. of Hg	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
0.635	0.25	15	29.78	1.028	15.7	22.2	29.2	41.3
			28.63	0.99	15.3	21.65	28.5	40.3
			27.73	0.957	14.9	21.1	27.7	39.2
			26.93	0.93	14.4	20.4	26.8	23.0
			25.93	0.895	14.0	19.8	26.0	36.8
			24.68	0.852	13.6	19.2	25.3	35.7
			23.63	0.818	13.2	18.7	24.6	34.8
			22.38	0.776	12.5	17.2	23.25	32.0
			21.58	0.745	12.1	17.1	22.5	31.8
			20.78	0.717	11.8	16.7	22.0	31.1
			19.88	0.686	11.3	16.0	21.0	29.8
			18.78	0.649	10.75	15.2	20.0	28.3
			17.88	0.618	10.4	14.7	19.35	27.4
			16.68	0.576	9.8	13.85	18.25	25.8
			15.73	0.544	9.26	13.1	17.2	24.4
			14.48	0.500	8.66	12.25	16.1	22.8

Barometer. 29.78 in.

TABLE X

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS

2.54-cm. DIAMETER SPHERES—NON-GROUNDED.

Spacing cm.	Spacing in.	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
3.81	1.5	1.01	52.4	74.2	29.2	41.4
"	"	0.962	50.5	71.5	28.1	39.8
"	"	0.923	49.1	69.5	27.4	38.7
"	"	0.875	45.7	64.6	25.5	36.0
"	"	0.834	45.2	64.0	25.2	35.7
"	"	0.798	42.8	60.6	23.8	33.8
"	"	0.757	41.3	58.5	23.0	32.6
"	"	0.734	40.4	57.2	22.5	31.9
"	"	0.722	39.0	55.1	21.7	30.7
"	"	0.669	38.0	53.8	21.2	30.0
"	"	0.629	35.6	50.4	19.8	28.1
"	"	0.590	34.1	48.3	19.0	26.9
"	"	0.551	32.7	46.3	18.2	25.8
"	"	0.527	31.2	44.3	17.4	24.7
"	"	0.487	30.5	43.2	17.0	24.1

TABLE XI

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS

5.08-cm. DIAMETER SPHERES—NON-GROUNDED

Spacing cm.	Spacing in.	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
5.08	2	1.018	78.4	111.0	27.4	38.9
"	"	0.98	75.6	107.	26.5	37.6
"	"	0.944	73.1	103.5	25.6	36.2
"	"	0.903	7.07	100.	24.8	35.0
"	"	0.872	68.7	97.2	24.0	34.0
"	"	0.836	64.	90.5	22.4	31.7
"	"	0.798	63.6	90.	22.3	31.5
"	"	0.764	61.1	86.4	21.4	30.2
"	"	0.726	58.9	83.3	20.6	29.2
"	"	0.682	56.1	80.5	19.6	28.2
"	"	0.654	54.0	76.4	18.9	26.8
"	"	0.618	51.5	73.0	18.0	25.6
"	"	0.578	49.0	69.3	17.2	24.3
"	"	0.544	45.8	64.7	16.0	22.6
"	"	0.510	43.3	61.2	15.2	21.4

TABLE XII

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS

12.5-cm. DIAMETER SPHERES—NON-GROUNDED.

Spacing cm.	Spacing in.	Relative air density	kv. eff.	kv. max.	g_s eff. measured.	g_s max. measured.
2.54	1	1.016	52.4	74.1	23.6	33.4
"	"	0.966	49.9	67.9	22.4	30.6
"	"	0.928	47.4	67.0	21.3	30.2
"	"	0.88	45.4	64.2	20.4	28.9
"	"	0.83	42.5	60.1	19.2	27.1
"	"	0.778	40.0	56.6	18.0	25.5
"	"	0.738	38.4	54.3	17.3	24.4
"	"	0.705	36.0	52.2	16.6	23.5
"	"	0.644	33.4	47.2	15.0	21.2
"	"	0.607	31.4	44.5	14.1	20.0
"	"	0.558	29.4	41.6	13.2	18.7
"	"	0.538	29.6	41.8	13.3	18.8
"	"	0.493	27.4	38.8	12.3	17.5

TABLE XIII

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS.

12.5-cm. DIAMETER SPHERES—NON-GROUNDED.

Spacing cm.	Spacing in.	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
5.08	2	1.02	91.	129.	23.	33.65
		0.962	87.4	123.5	22.1	31.25
		0.925	84.6	120.	21.4	30.40
		0.89	81.9	115.8	20.7	29.25
		0.846	78.1	110.5	18.73	27.95
		0.81	76.3	107.9	19.26	27.25
		0.754	71.6	100.	18.1	25.30
		0.707	66.	93.5	16.7	23.65
		0.661	64.1	90.6	16.2	22.90
		0.603	59.3	84.	15.0	21.25
		0.550	53.9	76.1	13.64	19.25
		0.532	52.0	73.5	13.15	18.60
		0.506	50.1	71.	12.65	17.95

TABLE XIV

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS.

12.5-cm. DIAMETER SPHERES—NON-GROUNDED.

Spacing cm.	Spacing in.	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
10.16	4	1.004	145.0	205.0	23.0	32.55
"	"	0.965	144.	203.7	22.85	32.30
"	"	0.93	139	196.6	22.10	31.20
"	"	0.90	137.	194.	21.78	30.80
"	"	0.865	131.8	186.5	20.95	29.65
"	"	0.859	131.5	186.2	20.85	29.60
"	"	0.793	123.7	175.0	19.60	27.80
"	"	0.762	120.8	171.0	19.20	27.20
"	"	0.739	115.7	163.6	18.36	26.00
"	"	0.685	110.2	156.0	17.50	24.80
"	"	0.67	105.9	149.7	16.80	23.75
"	"	0.623	100.	141.4	15.90	22.45
"	"	0.595	96.6	136.6	15.34	21.70
"	"	0.534	88.3	125.0	14.05	19.85
"	"	0.503	82.2	116.4	13.05	18.50

TABLE XV

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS.

12.5-cm. DIAMETER SPHERE—NON-GROUNDED.

Spacing cm.	Spacing in.	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
12.7	5	0.982	163.0	230.0	23.1	32.7
"	"	0.951	156.	221.0	22.2	31.4
"	"	0.917	150	212.5	21.3	30.2
"	"	0.88	147	208	20.9	29.5
"	"	0.846	143.5	203	20.4	29.8
"	"	0.807	139.5	197.5	19.8	28.0
"	"	0.78	134.5	190	19.1	27.0
"	"	0.736	131	185.5	18.6	26.3
"	"	0.699	125	177	17.7	25.1
"	"	0.666	120.5	170	17.1	24.2
"	"	0.637	115.5	163	16.4	23.1
"	"	0.598	109.5	155	15.5	22.0
"	"	0.561	104.5	147.5	14.8	21.0
"	"	0.541	101	142.5	14.3	20.2

TABLE XVI

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS

12.5-cm. DIAMETER SPHERES—NON-GROUNDED.

Spacing cm.	Spacing in.	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
20.32	8	0.938	198.5	281	23.0	32.6
"	"	0.912	197	279	22.9	32.4
"	"	0.874	189.5	268	22.0	31.1
"	"	0.842	183	259	21.2	28.9
"	"	0.804	176.5	250	20.5	29.0
"	"	0.767	169	239	19.6	27.8
"	"	0.737	163.5	231	19.0	26.8
"	"	0.704	157.5	223	18.3	24.7
"	"	0.674	151	235	17.5	24.8
"	"	0.615	140.0	198.0	16.2	23.0
"	"	0.568	130.5	184.5	15.1	21.4
"	"	0.528	120.5	171	14.0	19.8
"	"	0.488	110	157	12.8	18.2
		0.464	105.5	149	12.2	17.3

TABLE XVII

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS

12.5-cm. DIAMETER SPHERE—GROUNDED.

Spacing cm.	Spacing in.	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
6.35	2.5	0.908	95.5	135	21.2	30.0
		0.869	92.5	130.5	20.5	29.0
		0.828	88.6	125	19.7	27.8
		0.796	85.8	121	19.05	26.9
		0.758	81.1	114.5	18.0	25.4
		0.723	78.2	110.5	17.35	24.5
		0.69	73.2	103.5	16.25	23.0
		0.653	71.5	101	15.9	22.4
		0.62	68.2	96.3	15.15	21.4
		0.582	64.3	90.9	14.25	20.2
		0.539	60.7	85.8	13.5	19.05
		0.439	55.6	78.5	12.35	17.4

TABLE XVIII

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS.

25-cm. DIAMETER SPHERE—NON-GROUNDED.

Spacing cm.	Spacing in.	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
7.62	3	1.018	139	196.5	22.2	31.5
		0.978	133.5	189	21.4	30.3
		0.942	129.5	183	20.8	29.3
		0.906	126	178	20.2	28.5
		0.888	121.5	172	19.5	27.6
		0.839	115	163	18.4	26.1
		0.796	111	157	17.8	25.2
		0.752	105.5	149	16.9	23.9
		0.718	101.5	142	16.3	22.7
		0.685	96.2	136	15.4	21.8
		0.646	91.5	129.5	14.6	20.7
		0.608	87.0	123	13.9	19.7
		0.570	81.3	115	13.0	18.4
		0.527	74.7	105.5	12.0	16.9
		0.491	70.8	100	11.3	16 0

Figs. 4 to 8. The points are measured values. The drawn lines are calculated by multiplying the voltage values from the standard curves at $\delta = 1$, by the correction factor k.

$$k = \delta \frac{\left(1 + \frac{0.54}{\sqrt{\delta R}}\right)}{\left(1 + \frac{0.54}{\sqrt{R}}\right)}$$

The calculated values check the measured values very closely.

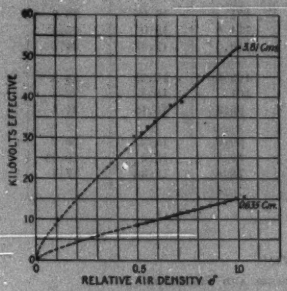

FIG. 4—SPARK-OVER VOLTAGE WITH VARYING AIR DENSITIES

2.54-cm. (1-in.) spheres. Non-grounded. Spacing 3.81 cm. (1.5 in.), 0.635 cm. (0.25 in.)

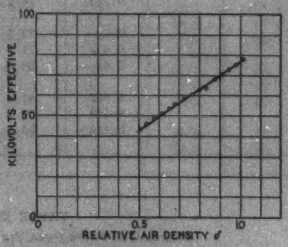

FIG. 5—SPARK-OVER VOLTAGE WITH VARYING AIR DENSITIES

5.08-cm. (2-in.) spheres. Non-grounded. Spacing 5.08 cm. (2 in.).

The equation for the correction factor was deduced from measured values as follows:

From a former investigation[7] it was found that at $\delta = 1$ the average gradient

$$g_s = g_0\left(1 + \frac{0.54}{\sqrt{R}}\right) \tag{1}$$

From the present investigation it was found that the average gradient at various values of δ is

$$g_s = g_0\,\delta\left(1 + \frac{0.54}{\sqrt{\delta R}}\right)$$

7. *Law of Corona III.* F. W. Peek, Jr., TRANS. A.I.E.E., Vol. XXXII, 1913, p. 1767. Discussion, TRANS. A.I.E.E., Vol. XXXII, 1913, p. 812.

The average measured gradients for various values of δ are given in Table XIX; values calculated from the equation are also given. The check is quite close. It should be remembered, however, that these are average values and that there is a small varia-

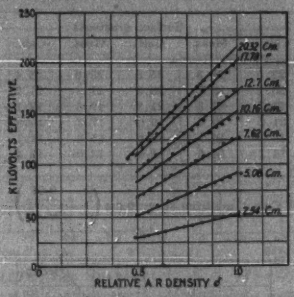

FIG. 6—SPARK-OVER VOLTAGE WITH VARYING AIR DENSITIES
12.5-cm. (4 15/16 in.) spheres. Non-grounded.

Spacing { 2.54 cm. (1 in.)
5.08 cm. (2 in.)
7.62 cm. (3 in.)
10.16 cm. (4 in.)
12.7 cm. (5 in.)
17.78 cm. (7 in.)
20.32 cm. (8 in.) }

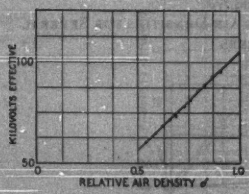

FIG. 7—SPARK-OVER VOLTAGE WITH VARYING AIR DENSITIES
12.5-cm. (4 15/16-in.) spheres grounded.
Spacing 6.35 cm. (2.5 in.).

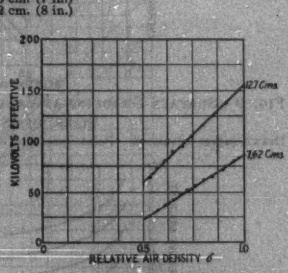

FIG. 8—SPARK-OVER VOLTAGE WITH VARYING AIR DENSITIES
25-cm. (9 7/8-in.) spheres, non-grounded.
Spacing { 12.7 cm. (5 in.).
7.62 cm. (3 in.). }

tion at different spacings over this range, as already explained. (See Figs. 9 and 10).

FREQUENCY

Over the commercial range there is no variation due to frequency. Fig. 11 shows spark-over curves up to 25 kv.

TABLE XIX

AVERAGE EFFECTIVE RUPTURING-GRADIENTS FOR SPHERES OF SEVERAL DIAMETERS AND VARYING AIR DENSITIES.

δ	Diameter of Spheres, cm.							
	2.54		5.08		12.5		25	
	Surface gradients							
	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.
1.00	28.7	28.5	25.8	25.8	23.6	23.4	22.0	22.2
0.90	26.2	26.1	23.7	23.3	21.8	21.2	19.9	20.1
0.80	24.0	23.7	21.3	21.3	19.6	19.1	17.9	18.0
0.70	21.3	21.2	19.0	19.0	17.4	16.9	15.7	15.9
0.60	18.7	18.7	16.7	16.6	15.2	14.7	13.6	13.8
0.05	16.1	16.1	14.6	14.3	13.0	12.5	11.6	11.7

Columns marked "Calc." are from $g_s = 19.3\,\delta\left(1 + \frac{0.54}{\sqrt{\delta R}}\right)$

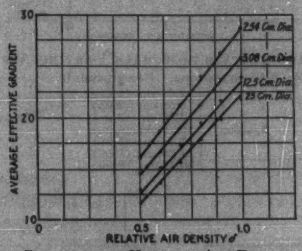

FIG. 9—SURFACE GRADIENT AT VARYING AIR DENSITIES FOR SEVERAL SIZES OF SPHERES

Drawn curves calculated. Points measured values:

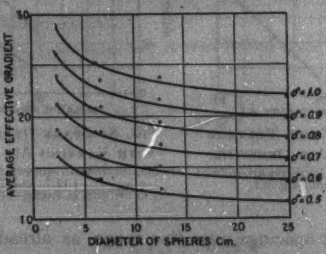

FIG. 10—SURFACE GRADIENT FOR VARYING SIZES OF SPHERES AT SEVERAL AIR DENSITIES.

Drawn lines calculated from formula $g_s = 19.3\,\delta\left(1 + \frac{0.54}{\sqrt{\delta R}}\right)$

Points measured values.

with 1000-cycle sine-wave current from an alternator. The voltage was measured by a static voltmeter calibrated at 60 cycles. The drawn curve is the 60-cycle curve and the points are measured values. Fig. 12 gives a 60-cycle curve, and also a 40,000-cycle curve from a sine-wave alternator.

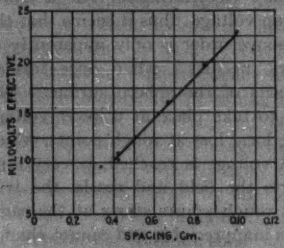

FIG. 11A—SPHERE GAP SPARK-OVER VOLTAGE AT 60 CYCLES AND 1000 CYCLES

5.08-cm. diam. spheres. Drawn curve 60 cycles. Points taken at 1000 cycles.

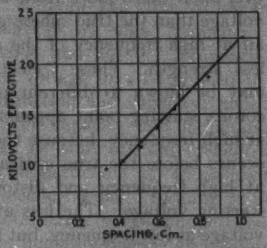

FIG. 11B—SPHERE GAP SPARK-OVER VOLTAGE AT 60 CYCLES AND 1000 CYCLES

12.5-cm. diam. spheres. Drawn curve 60 cycles—points taken at 1000 cycles.

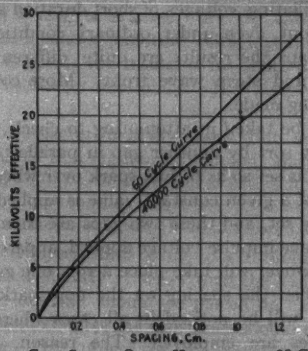

FIG. 12—SPHERE GAP SPARK-OVER VOLTAGE AT 60 CYCLES AND 40,000 CYCLES

Points measured at 40,000 cycles. 5.08-cm. (2-in.) spheres, not polished.

The voltage in this case was measured by a static voltmeter. No special care was taken to polish the sphere surfaces. At low frequencies, at rough places on the electrode surface there is local over-stress, but even if the air is broken down, the loss at these places is very small and the streamers inappreciable.

At continuous high frequency, a local breakdown at a rough point probably takes place at the same gradient as at 60 cycles, but the energy loss after the breakdown at this point occurs may be 1000 times as great. This forms a needle-like streamer which increases the stress and local loss. Spark-over then takes place from this "electric needle" at a lower voltage than the true sphere gap voltage; thus it seems that the air at high frequency of the above order is only apparently of less strength. These "electric needles" when once formed may be blown to different parts of the sphere surface. The corona starting point appears to take place at a lower voltage at high frequency, because the local loss at rough points, which occurs before the true critical voltage is reached, is very high at high frequency and distorts the field and masks the true starting voltage. The loss at rough points starts at the same voltage at low frequency, but is inappreciable and cannot change conditions. If the sphere surfaces are very highly polished it seems that the high-frequency spark-over voltage should check more closely with the 60-cycle voltage for frequencies of the above order. It also seems that the curves should check very closely for oscillating voltages of short duration and voltages of steep wave front, even under ordinary conditions of surface. With needle gaps the results are quite different at high and low frequency and steep wave front. More complete investigations are being made.

Care should be taken in attempting to check voltages across one gap of any sort by another gap in parallel. For instance, if a needle gap is set so as to just spark over when a steep wave-front voltage of a given constant value is applied, and a sphere gap is similarly set, and these two gaps are then placed in parallel and the same impulse voltage applied, apparent discrepancy results. Spark-over will take place across one gap and not the other, even when the spacing on the non-sparking gap is decreased. This will be noticed in all cases where electrodes of different shapes are employed. The reason, apparently, is that energy is necessary to start rupture in the dielectric, the amount of energy varying with the shape of the electrode. This introduces a time element which differs for different gaps. Thus, in this case the "fastest" gap will spark over and relieve the voltage before the other has time to spark, even if the other gap is decreased.

It is now often said that "high frequency acts differently, on insulation, from low frequency". When the time of applica-

tion is sufficiently short, say a few cycles, so that the effect of heating may be neglected, and the circuit is such that local concentration of potential is not possible, it is probable that a given high-frequency potential is less destructive than the same low-frequency potential. For steep wave fronts a higher voltage is required to spark over a given gap than for low frequency. Destruction of insulation by high frequency is generally due to local over-voltage, and not to "frequency". For instance, high-frequency low voltage may be applied to a piece of apparatus containing induction and capacity, such as a transformer. On account of the capacity and inductance, very high local over-voltage may be built up, and breakdown results, due to over-voltage. The petticoats of an insulator may be broken down by an "electric needle" forming as described above, and bringing the total stress on the thin petticoat.

Spectacular tests are sometimes made by placing an insulator in multiple with a gap over which an oscillatory discharge is taking place, such as a Tesla coil gap. This gap is set at a spacing that would limit the voltage to a safe voltage at 60 cycles, yet the insulator is punctured on the oscillatory discharge. This is not remarkable. By the circuit arrangement *many* times the insulator puncture voltage is applied to the gap. This voltage is across the insulator for short intervals just before the gap discharges take place. It is simply a case of over-potential.

Such tests are useful in many cases, but are dangerous to apparatus unless thoroughly understood and necessary precaution taken.

Precautions against Oscillations in Testing

A non-inductive resistance of one to four ohms per volt should always be placed directly in series with the gap. For the non-grounded gap, one-half should be placed on each side. When one gap is grounded, all of the resistance should be placed on the insulated side. One object of the resistance is to prevent oscillations from the test piece, as a partial arc-over on a line insulator, reaching the gap. Accuracy cannot be secured without this resistance. Another object is to limit the current discharge. This resistance is of special importance when tests are being made on apparatus containing inductance and capacity. If there is no resistance, when the gap sparks over, oscillations will be produced which will cause very high

local voltage rise over parts of the winding. If sufficient resistance is used, these oscillations will be damped out. This is illustrated in Fig. 13, which shows results of a test on a high-voltage transformer on which a 19-cm. gap test is required.

Referring to Fig. 13, the high-voltage winding of the transformer under test is short-circuited and connected to one terminal of the testing transformer. The other terminal of the testing transformer is grounded. The low-voltage winding of the transformer under test is short-circuited, connected to the case and ground. Voltage is gradually applied to the trans-

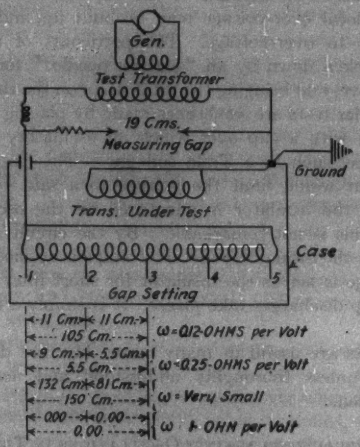

FIG. 13

former under test until the "measuring gap" sparks over. Insulated taps, 1, 2, 3, 4, 5, are brought out at equidistant points from the high-tension winding of the transformer under test. Auxiliary needle gaps are placed between 1 and 2, 2 and 3, and 1 and 3, to measure the voltage which appears across these sections of the winding when the main measuring gap discharges. The numbers on the figure between 1–2, 2–3 and 1–3, represent the sparking distances of the local voltages caused by a discharge of the measuring gap. Four cases are given with different values of resistance ω in the main gap. When

ω equals one ohm per volt the local voltages are completely damped out.

With small resistance in the main gap, a 19-cm. spark-over causes a voltage to build up between coils one and three which sparks over a 150-cm. gap, although the total applied voltage across the transformer is only equivalent to a 19-cm. gap. The apparatus may thus be subjected to strains far beyond reason, and either broken down or very much weakened. Water-tube resistance is the most reliable. A metallic resistance, if non-inductive and of small capacity, may be used. Carbon or graphite rods should be avoided, because, although they may measure up to a very high resistance at low voltage, the resistance may become very low at high voltage by "coherer" action. Where possible the gap should be used only to measure the equivalent transformer ratio and not during test. When the tested apparatus is of such nature that there is considerable incipient arcing before spark-over, it is better to use the spheres to determine the "equivalent ratio" of the transformer below the voltage at which this arcing occurs. It must be remembered that resistances do not dampen out low-frequency surges resulting from a short circuit, etc.

TABLE XX.

POSSIBLE PER CENT ERROR DUE TO PLATES ON 6.25-CM. SPHERE SHANKS.

Spacing cm.	Non-grounded 5 cm. diameter plate 6.25 cm. back of		Grounded 5 cm. diameter plate 6.25 cm. back of		
	both spheres	one sphere	insulated sphere	grounded sphere	both spheres
1.5	0	−0.2	+0.7	−0.7	0
3.0	+1.0	−1.0	+1.5	−1.5	+2.0
6.0	+2.0	−2.0	+3.0	−2.0	+2.0

This table is not meant for making corrections. The arrangement should be such that no corrections are necessary.

APPROXIMATE EFFECT OF DISTANCE ABOVE GROUND WHEN ONE SPHERE IS GROUNDED

Diameters of grounded sphere above ground.	Percentage variations from standard curves for different spacings.		
	$X = 2R$;	$X = R$;	$X = R/2$
0	−10.	5.5	0.0
1	− 4.5	−3.0	0.0
2	− 2.	−1.0	0.0
3	− 1.	−0.5	0.0
4	0.	0.0	0.0
5	+ 0.5	+0.3	0.0
6	+ 1.0	+0.5	0.0
10	+ 2.5	+1.0	0.0
20	+ 2.5	+1.0	0.0

Miscellaneous Precautions

In making tests it is desirable to observe the following precautions:

The shanks should not be greater in diameter than 1/5 the sphere diameter. Metal collars, etc., through which shanks extend, should be as small as practicable, and should not come closer to the sphere than the gap length. For the non-grounded case the effect of such objects is a minimum when symmetrical on either side. For the grounded case the effect is considerable. The effect of a large plate or plates on the shanks is given in Table XX. This should show the maximum error in all cases, as the maximum gap setting, and the extreme diameter of collar that is likely to be used in practise, is taken. The sphere diameter should not vary more than 0.1 per cent, and the curvature, measured by a spherometer, should not vary more than 1 per cent from that of a true sphere of the required diameter. The spheres should be twice the gap setting from surroundings.

In Table XX the spacing X is given in terms of radius R, to make the correction applicable to any size of sphere. The distance of the grounded sphere above ground is, for the same reason, given in terms of the sphere diameter. The (+) sign means that a higher voltage is required to arc over the gap than that given by the standard curve. The (−) sign indicates that the spheres read too low. The standard curves were made with the grounded spheres from four to five diameters above ground. In practise it is desirable to work between four and ten diameters; never under three. Above ten the variation in per cent error remains about the same.

When both spheres are insulated, with the transformer neutral at the mid point, there is practically no variation in voltage for different distances above ground.

Great precautions are necessary at very high voltages to prevent leakage over stands, supports, etc., and to prevent corona and brush discharges. Care must also be taken to so place the spheres that external fields are not superposed above the sphere gap. This is likely to result, especially in the non-grounded case, from a large mass of resistance units or connecting leads, etc., in back of and in electrical connection with either sphere. The error may be either plus or minus, as indicated for the small

plates in Table XX. With the water-tube resistance this condition is not likely to obtain, as the tube may be brought directly to the sphere as an extension of the shank.

The author wishes to acknowledge the assistance of Mr. H. K. Humphrey in laboratory work and in making calculations.

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THE ELECTRIC STRENGTH OF AIR—V
The Influence of Frequency

BY J. B. WHITEHEAD AND W. S. GORTON

ABSTRACT OF PAPER

The paper presents the account of an investigation of the influence of frequency on the corona, between 60 and 3000 cycles per second. The wire and coaxial cylinder method was used.

A simple method for measuring the maximum value of an alternating voltage wave has been developed and used for obtaining this maximum value at the critical corona voltage. The gold-leaf electroscope was used to detect the first appearance of corona.

It has been found that for frequencies above 275 cycles per second the corona voltage (maximum value) is not so uniform and constant as it is at frequencies in the neighborhood of 60 cycles.

The indications of the investigation are that at 2000 cycles the corona voltage is lower than it is at 60 cycles by about 3 or 4 per cent.

The experiments reveal several interesting instances of resonance phenomena in the high-tension transformer circuits.

IN AN earlier paper by one of the authors[1] it was shown that within the range 20 to 90 cycles per second the frequency had a measurable effect on the voltage (maximum of the wave) at which the corona begins. The principle of the method of experiment is simple and will be repeated briefly here. The corona is formed about a wire which is stretched coaxially in a metal cylinder, the ends of the cylinder being closed by insulating bushings. Air may be let into the cylinder by a lateral tube near one end and out by a lateral tube near the other end. Immediately after leaving the cylinder the air passes over an insulated electrode which is connected to a gold-leaf electroscope. The walls of the cylinder where the lateral tubes were connected were drilled with numerous small holes. The air could thus pass freely and at the same time the electrode could not be influenced electrostatically by the presence of the highly charged wire at the axis of the cylinder. As the voltage applied to the wire

1. Whitehead, TRANS. A.I.E.E., 1910, Vol. XXIX, Part II, p. 1159; and 1911, Vol. XXX, Part III, p. 1857.

is gradually raised, a value is reached at which the air around the wire is ionized, that is, becomes conducting. The electroscope, as soon as this occurs, begins to lose its charge. The cylinder was always connected to earth.

It was found that the point at which the electroscope began to leak was the same whether the air was moving through the tube or whether the air was at rest, and that initial ionization and the visual corona were always contemporaneous. It was shown, too, that for a given size wire and tube under the same conditions of temperature and pressure, the corona always began when the voltage in its cycle reached a definite value and that this value was approximately the same as the maximum value of the voltage at which the electroscope first began to leak. Another result was that the electric field strength at the surface of wire when corona began was independent of the size of the tube.

The value of the voltage delivered by the high-tension side of the transformer was determined from the ratio of transformation and from oscillograms taken of the voltage impressed across the low-tension terminals of the transformer. It was assumed that the wave shape of the high-tension e.m.f. was the same as that of the low-tension e.m.f.

The uniform appearance of the corona at a definite value of voltage, regardless of position on the wave, would seem to indicate that the corona voltage should be independent of the frequency. This, however, was not borne out by the experiments. The corona voltage was found to decrease with increasing frequency. A curve plotted between frequency and the maximum value of the voltage wave for the critical voltage (*i.e.*, beginning of corona) showed a fairly regular decrease from 20 cycles to 90 cycles. This decrease had the same percentage value for the various sizes of wire tried. The voltage at 90 cycles was about 6 per cent lower than the voltage of 20 cycles.

The influence of frequency has been studied by comparatively few investigators, and far from completely. Peek[2], in the range 40 to 100 cycles per second, was unable to detect any influence of frequency either on the voltage at which the visual corona started or on the voltage at which the loss began. Very recently Alexanderson[3] has found that at 100,000 cycles per second, a 3-in. (76.2-mm.) spark gap between spheres 5 in. (127 mm.) in diameter breaks down at approximately the same voltage (100,000 volts)

2. Peek, TRANS. A. I. E. E., 1912, Vol. XXXI, Part I, p. 1055.
3. Alexanderson, *General Electric Review*, page 427, April 1914.

that it does at commercial frequencies; a 5-in. gap between plane parallel plates, however, was found to break down at 30,000 volts—a much lower value than the breakdown voltage for commercial frequencies. Recent results of Weidig and Jaensch[4] indicate that for increasing values of voltage above the corona-forming voltage, the corona starts at a lower and lower and ends at a higher and higher instantaneous value; this is at variance with the observations reported in an earlier paper of this series and referred to above.

The work of the present paper was undertaken in order to extend the observations of the corona voltage over a wider range of frequency.

Experimental Apparatus

The generator available, although structurally a unit (direct-driven) consisted in fact of two generators; one having 48 poles and the other 240 poles. At the rated full speed, 1500 rev. per min., one generator gave 600 cycles and the other 3000 cycles per second. Each machine was rated at 110 volts, 5 amperes. Two transformers were used, one rated at 500 watts, 100/10,000 volts at 133 cycles per second, and a second, employed in the larger part of the work, rated at 3000 watts at 60 cycles. The low-tension winding of the latter transformer was in two 50-volt sections; the high-tension winding was in four sections, the rated voltage per section being 6250 volts.

The high-frequency generator was driven by a d-c. 240-volt shunt motor. The field of the generator was supplied from a 120-volt storage battery. The large amount of inertia possessed by the revolving field of the generator prevented any sudden changes in speed due to changing voltage of the direct-current supply. The conditions were thus favorable to steadiness in the readings. The speed of the generator was controlled partly by the use of resistance in the motor armature circuit and partly by varying the resistance of the motor field circuit.

Speeds from normal to three-quarters normal were obtained by the use of armature resistance; speeds from three-quarters to half normal were obtained by running the motor armature from the 120-volt mains and by the use of resistance in the field circuit. It was not feasible to run the machine at any speed much below half speed, because of the large field current required by the generator, and because of speed fluctuations. Control of

4. Weidig and Jaensch, *Electrotechnische Zeitschrift*, Heft 23 and 24, 1913.

the transformer voltage was effected by varying the field current of the generator.

The corona apparatus proper consisted, as in the earlier experiments, of a wire stretched coaxially in a metal tube. At a point equidistant from the ends of the tube were drilled numerous small holes (about $\frac{1}{8}$ in. (3.2 mm.) in diameter). The electrode, which consisted of a brass disk having the same curvature as the tube, was placed over these holes and as near the tube as could conveniently be done without having metallic contact. A grounded metallic shield was placed around the electrode and the connection to the electroscope was made through a hole in the shield, the wire being insulated from the shield by means of a plug of sulfur. The electroscope was a very sensitive one; it gave a workable deflection of the gold-leaf when charged to a potential of 120 volts. In the earlier part of the work the ends of the tube were left open, the wire being stretched between insulating supports situated at some distance from the ends of the tube. Later the ends of the tube were closed by insulating caps, the wire passing through holes in the caps.

The Experiments

Observations were first made on a brass wire 0.089 cm. (0.0350 in.) in diameter in a 4.9-cm. tube. The 500-watt transformer mentioned above was used. The procedure was to raise the primary voltage by increasing the field current of the generator until the electroscope began to discharge. The field current was then decreased until the leak of the electroscope stopped, and then increased again. The voltage at the instant the leak began was read by a hot-wire voltmeter, connected across the low-tension terminals of the transformer. The speed was read by a carefully calibrated tachometer. No attempt was made in these experiments to determine the wave shape, this being a matter of some difficulty at the frequencies in question. In the neighborhood of 600 cycles, the electroscope began to leak at about 80 volts, at 1400 cycles at 73 volts and finally, at 2800 cycles, at 37 volts. The decrease in voltage between 1400 and 2800 cycles was fairly regular.

It seemed highly improbable that the corona voltage actually experienced as great a change as was indicated by the above figures. To test the matter further, a high-tension electrostatic voltmeter was connected across the high-tension terminals of the transformer.

It was found that the corona voltage as indicated by the static voltmeter remained constant. The corona tube was then disconnected from the transformer and at various frequencies the voltage was adjusted so that this voltmeter always read 10 kilovolts. At 60 cycles the low-tension voltage was 82.5 volts, and at 2750 cycles, 31 volts. It was thus seen that the ratio of transformation of this transformer was *over two and one-half times* as great at 2750 cycles as it was at 60 cycles. The cause of this great change is evidently the capacity of the high-tension windings. The charging current taken by the high-tension windings, other things being equal, is directly proportional to the frequency. The reactance of these same windings is also directly proportional to the frequency. Consequently one would expect the disturbing effect of the charging current on the ratio of transformation to be, roughly, directly proportional to the square of the frequency.

That the current taken by the transformer was leading was easily shown. An electrodynamometer connected in the low-tension side indicated 5.5 amperes at 2750 cycles—ten times the value of the current taken at 60 cycles for the same high-tension voltage. The large reactance of this instrument (22 ohms at 2750 cycles) was in this instance of great advantage, because by applying the three-voltmeter method to the dynamometer and transformer the relative power factor of the two could be at once determined. The power factor of the dynamometer alone was determined by series connection with incandescent lamps (assumed non-inductive) and applying the same method. It was found that the current taken by the transformer at 2750 cycles was leading the voltage by about 60 degrees.

For further study of this disturbing influence, tests were made with the 3000-watt transformer described above. The high-tension voltage was not measured, but the effect of different methods of connection of the high-tension coils was studied. All the experiments were conducted at about 2750 cycles. A few examples of the results may prove of interest. With all the high-tension windings in series; one end of the winding connected to ground and the other end open, the transformer took 3.1 amperes at 3.5 volts, the current leading the voltage by about 20 degrees. With the high-tension windings connected two in series, two in parallel, the same point being earthed as formerly, the transformer took 4.0 amperes at 33.5 volts. the current leading the voltage by about 90 degrees. In both cases the low-

tension windings were in series. These two cases are fair samples of the results found in the course of the experiments, and indicate that the method of connecting the high-tension windings has a pronounced influence on the readings of the instruments in the primary side of the transformer.

There was also evidence that at one frequency within the range studied, the transformer was in resonance. With a certain arrangement of the high-tension windings and running at 2750 cycles the switch of the driving motor was opened. With the resulting decrease of speed and frequency, the voltage applied to the transformer and the current taken by it both began to increase and kept on increasing until it was necessary to open the transformer circuit in order not to injure the instruments. There were also indications that the principal factor in these effects was the capacity between winding and core and not between successive portions of the winding. It was found, for example, that the readings on the low-tension side of the transformer depended only upon the maximum voltage (from ground) reached in the high-tension winding. The effect produced by connecting all the coils in series and grounding the middle point of the winding was the same as that produced by connecting the windings two in series and two in parallel and grounding one end.

It appears probable from the results of this paper that the 6 per cent lowering of the corona voltage in going from 20 to 100 cycles reported in the second of this series of papers may be explained as a disturbance due to the capacity in the transformer; all measurements in that work were made on the low-tension side.

Measurement of Maximum Value of Voltage

It was at once evident, from the results of the tests described above, that the measurements of corona voltage would have to be made on the high-tension side of the transformer. This condition, coupled with the unreliability of the oscillograph for the higher frequencies, made it impossible to obtain complete knowledge of the wave shape, except, perhaps, by the use of the cathode ray oscillograph. It is possible, however, to measure both maximum and effective values. Obviously the former is the more important, and probably the determining factor in the formation of corona. The only method available for finding the maximum value is that used by Chubb and Fortescue.[5]

5. Chubb and Fortescue, Trans. A. I. E. E., Vol. XXXII, 1913, p. 739.

among others. The method consists essentially in applying the voltage to be investigated to a condenser and measuring the average value of the current taken by the condenser. Let V represent the maximum value attained by the voltage, C the capacity of the condenser and f the frequency. The time taken by the voltage in passing from its maximum value in one direction, to its maximum in the other, is $\frac{1}{2f}$. In this time the current goes from zero to a maximum and back to zero again. Its average value is equal to the total charge which has passed through the circuit, divided by the time taken for the charge to pass. In symbols:

$$i_{av} = \frac{1}{\frac{1}{2f}} \int_0^{\frac{1}{2f}} i\,dt = \frac{2VC}{\frac{1}{2f}} = 4fVC.$$

$$V = \frac{i_{av}}{4fC} \tag{1}$$

In order to measure the average value of the charging current taken by the condenser, it is necessary to employ a measuring instrument of the permanent magnet type and to rectify the current before it passes into the instrument, or, what amounts to the same thing, to allow only one-half of the current wave to pass through the instrument; in this latter case the reading of the instrument must be multiplied by 2 in order to get the average value of the current. Chubb and Fortescue made use of a mechanical device in order to have only one-half of the current wave pass through the measuring instrument. In the present work the use of a mechanical device was out of the question on account of the high frequencies employed. The mercury arc immediately suggests itself as a non-mechanical rectifier. The rectifying properties of the mercury arc when playing between a mercury and an iron electrode are well known. The arc permits current to flow from the iron electrode to the mercury with only a trifling drop of voltage in the arc; no current can flow in the opposite direction until the applied voltage has risen so high as to cause a vacuum discharge to pass through whatever gas may be present. The mercury arc, moreover, is very rapid in action. It has been shown, for example, that the arc will

be extinguished if the current supply is interrupted for as much as the ten-millionth part of a second. Thus the ionization or conductivity due to the passage of the current dies out with enormous rapidity.

In the present experiments the current taken by the condenser could not itself be used to maintain the arc, first, on account of its small value, and second, because of the necessary method of connection (see Fig. 2). As a consequence the cathode had to be kept active by an arc (maintained by direct current) playing between the cathode and an auxiliary mercury anode. The form of tube which was adopted after considerable experimenting is illustrated in Fig. 1. The tubes were made from German soft glass tubing having approximately an internal diameter of 1 cm. and walls 1 mm. thick. The iron electrode consisted of about 6 cm. of No. 30 iron wire which had been well oxidized by passing through the flame of a blast lamp. The object in making the iron electrode so small was to prevent mercury from condensing on it. In an earlier form of tube the iron electrode was much larger, with the result that mercury condensed on the electrode and dropped off.

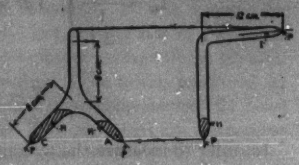

FIG. 1

P, platimum wire; I, iron wire; M, mercury; C, cathode; A, anode.

This last action interfered seriously with the proper functioning of the tube, as, at every fall of a drop, an arc would be started, irrespective of the direction of the voltage acting across the gap. A small wire assumes the temperature of the surrounding mercury vapor much more quickly, consequently condensation is much reduced. The electrode was oxidized in order to prevent the amalgamation of the iron and the condensed mercury. The presence of such an amalgamated surface seems to facilitate condensation enormously. The tubes were exhausted while running until the pressure of the residual gas was less than 0.0001 mm.

A diagram of connections is shown in Fig. 2. It will be seen that during one half of the wave the charging current of the condenser passes through one of the two tubes, and during the other half, through the other tube. A direct-current voltmeter was used as a current-measuring instrument. This voltmeter was in circuit with one of the tubes; consequently, in

order to get the average value of the current its reading must be multiplied by 2. The voltmeter gave full scale deflection for a current of approximately 0.01 ampere. The 1.5-volt scale (resistance approximately 156 ohms) of the instrument was used; there was no difference in reading, however, when the 150-volt scale was used instead. The instrument gave the same reading, no matter with which tube it was in circuit; the reading was also unaffected by the presence of a similar instrument in series with the other tube. Each tube, moreover, was carefully tested for the degree of rectification. When the arc was playing between the two mercury electrodes a 240-volt difference of potential was applied between the mercury cathode and the iron electrode, suitable resistances being in the circuit for protection. When the iron electrode was positive with respect to the mercury cathode there was passage of current and the drop of potential across the tube was about 50 volts,

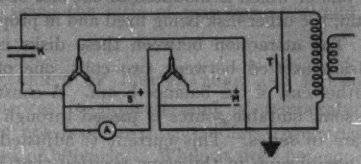

FIG. 2

A, voltmeter; S, special generator; K, condenser; M, city mains; T, corona tube.

independent of the value of current. When the iron electrode was negative with respect to the mercury cathode, the voltmeter showed no deflection and the use of a sensitive galvanometer showed that the current flowing was not greater than the five-millionth part of an ampere. As the tubes were used to rectify currents of the order of magnitude of 0.01 ampere, the rectification was thus practically perfect. Finally, the tubes were set up in series with a condenser, as shown in Fig. 2, and tested at various frequencies from 45 to 75 cycles. The assumption was made that in this range of frequencies the ratio of transformation remained constant and that the wave shape of the high-tension e.m.f. was the same as that of the low-tension e.m.f. The low-tension wave form was taken from oscillograms. The values of the maximum high-tension voltage as measured directly by the mercury tubes, and as calculated from the ratio of transformation and low-tension read-

ings, were the same, within the probable error of the measurements.

Measurement of Effective Value of Voltage

While the knowledge of the maximum value of the voltage so obtained seemed of greatest importance, it was also considered desirable to determine the effective value so as to obtain an approximate indication of the wave form, and ratio of transformation. Concerning minor irregularities on the wave nothing, of course, can be said. An electrostatic voltmeter seemed to be the most suitable instrument. An instrument was needed which would give the effective value of the voltage to ½ of one per cent or better, and which at the same time could be easily damped. These requirements suggested a Crémieu electrostatic-electrodynamic balance. The principle of this instrument is as follows: The voltage to be measured is applied to two disks, one of which is mounted at the end of one arm of a balance beam, the other disk being fixed and in proper relation to the first. The attraction between these disks is balanced by the repulsion exerted between two coils, one of which is fixed at the other end of the balance beam. A constant direct current from some suitable source is passed through these two coils, which are in series. This current is adjusted until the balance is in equilibrium in the same position that it occupies when no electric or magnetic forces are acting. The moment of the electric forces about the knife edge varies directly as the square of the voltage between the disks, and the moment of the magnetic forces varies directly as the square of the current flowing in the coils. Consequently when the balance is brought into the proper position of equilibrium the voltage between the disks is directly proportional to the current flowing in the coils. If, as in the present case, the voltage is alternating, the moment is proportional to the average square of the voltage, which is by definition the square of the effective value. Hence the effective value of the voltage is directly proportional to the current flowing in the coils.

The authors were fortunate in having available a balance beam with a fine agate knife edge, and the usual mounting. All magnetic material had been carefully excluded from the construction of the balance and its glass case. The disks were of aluminum and were 10 cm. in diameter. The distance between the fixed disk and the moving disk was 3.2 cm. The

moving coil consisted of 50 turns of No. 18 copper wire. The fixed coil had 1200 turns of No. 18 wire. The current was led into the moving balance system by means of two silver strips each 0.0013 cm. (0.0005 in.) thick, 1 mm. wide, and 6 cm. long. The points of support of a strip were 4 cm. apart, so that the strip had a very considerable sag. These silver strips would carry about 3.5 amperes before burning out. The largest current they were ever called on to carry was about 1 ampere; with this value of the current the heating of the strips was never enough to cause any disturbance of the balance due to air currents. The strips also had no effect on the sensibility of the balance, nor on the stability of the zero point. In using the balance, current for the coils was taken from a storage battery. When the voltage applied to the disks was steady, readings could be repeated to within ¼ of one per cent. When the voltage was unsteady, differences as great as one per cent frequently occurred. The balance was standardized at low frequencies, using the ratio of transformation and low-tension wave form.

Influence of Temperature and Pressure

The influences of pressure and of temperature upon the corona have not been investigated for frequencies above the neighborhood of 60 cycles. While it does not appear probable from the theory of ionization by collision that these influences would suffer any change up to 3000 cycles, it is nevertheless a matter of some uncertainty. Therefore, in order to determine the influence of frequency alone, it was necessary to make observations over the whole range of frequency within a period of time during which the pressure and temperature remained reasonably constant. Three hours was adopted as the length of such a period. This procedure made rather small the number of different frequencies at which it was possible to make observations, but the number of points obtained was sufficient to give a good knowledge of the variation with frequency. In order to shorten the time required for each reading only the maximum of the high-tension voltage wave was read when making observations on the corona. The effective values corresponding to the maximum voltages used were determined after the corona readings, thus greatly facilitating the work, as the effective values of all the different voltages used over the whole range of frequencies were readily determined in a

day. Referring again to Fig. 2, the voltage on the low-tension side of the transformer was read by a Hartmann and Braun hot-wire voltmeter, the series resistance of which was specially wound to avoid change in resistance with frequency. The speed of the generator was read by a carefully calibrated tachometer, accurate within ½ to 1/10 of one per cent, depending on the part of the scale used.

Calibration of Condensers

The condensers used were of the Moscicki type; the dielectric was glass and the condensers were filled with oil to avoid corona at the edges of the metallic coatings. Each condenser had a capacity of about 0.002 microfarad. Now the range of frequency used was from 60 to 3000 cycles, a 50-fold increase. A glance at equation (1) will show that if V stays approximately constant over this range (as it actually does) i_{ov} will be proportional to the frequency for constant capacity. This state of affairs would mean an enormous variation of the accuracy with the frequency. In order to avoid such a condition the capacity must be varied with the frequency in such a way as to keep the needle of the current-measuring instrument in a suitable part of the scale. This was done by using one condenser at 60 cycles, seven condensers in series for the range from 300 to 600 cycles, and all sixteen condensers in series for the range from 1500 to 3000 cycles. Even with the capacity reduced as much as possible by this means, it was impossible with the larger sizes of wires to go much beyond 1500 cycles, because the rectified current became larger than could be measured by the voltmeter employed; the use of a shunted instrument was, of course, out of the question.

The corona voltage at 60 cycles has been often observed; consequently it was sufficient in the present work to determine how the corona voltage varied with frequency. To this end only the *relative* values of the capacities of the condensers need be known. A special motor-driven generator, excited by a storage battery, furnished alternating current at about 45 cycles. The voltage was measured by an electrodynamometer-type voltmeter. The frequency was measured by a Hartmann and Braun vibrating-reed frequency meter. Condenser No. 1 was put in position in the connections of Fig. 2 and the low-tension voltage, frequency, and rectified current read. From seven to nine observations were made on each condenser. Then,

keeping the frequency, excitation, and all other conditions the same, No. 1 condenser was disconnected and No. 2 connected in its place; then No. 3, and so on for all sixteen condensers. Since the condensers were of approximately the same capacity and the conditions were kept constant, the maximum value of the high-tension voltage was directly proportional to the effective value of the low-tension voltage, and consequently the value of low-tension voltage could be substituted for V in the formula

$$C = \frac{i_{av}}{4fV}$$

in order to find the comparative values of the capacities. The capacity of condenser No. 1 was taken as the unit. The capacity of the condensers when connected in series could be calculated by the usual formula. The needle of the direct-current instrument vibrated with the frequency of the rectified current, the amplitude being about one-half of a division; on this account the accuracy of the reading was only ½ per cent. The frequency could be read to ½ per cent and the alternating voltage to 0.1 per cent. The accuracy of any one reading was consequently about 0.7 per cent. Since from seven to nine readings were taken, the final accuracy attained was about 0.3 per cent. Repeated measurements on one condenser showed that this was actually the order of accuracy attained.

Sizes of Wires and Tubes

Two sizes of corona tubes were used in the course of the experiments, one having a diameter of 4.58 cm. and the other a diameter of 6.35 cm. The diameters of the wires used were as follows: 0.317 cm. (0.1249 in.), 0.234 cm. (0.0924 in.), 0.194 cm. (0.0763 in.), 0.164 cm. (0.0644 in.), 0.106 cm. (0.0418 in.), 0.089 cm. (0.0350 in.). All of these sizes were of brass, except the wire 0.194 cm. in diameter, which was of tool steel. The smaller sizes were made straight by heating with an electric current while under tension. The larger sizes were rods which needed no such treatment. Each time before being used the wire was polished with the very finest emery paper until the latter became glazed with brass. A final polish was given with tissue paper. This treatment produced a very good polish. In the earlier part of the work the tube was left open at the ends; for the most part, however, the ends were closed with insula-

ting caps. No difference between the two cases could be detected.

Accuracy of Observations

The rectified current could be read to 0.1 per cent at frequencies of 300 and more, the needle standing without vibration. The speed could be read always to $\frac{1}{2}$ per cent and generally still more closely. The capacity of the condensers had been determined to 0.3 per cent. Consequently any one observation of the maximum voltage at 300 cycles and over was accurate to 0.6 per cent. At 60 cycles the rectified current could be read to $\frac{1}{2}$ per cent, the frequency (the generator was not readily accessible) to $\frac{1}{2}$ per cent, and the capacity, as before, was determined to 0.3 per cent. The accuracy was consequently at 0.8 per cent. For convenience, the current required to deflect the direct-current voltmeter one scale division, and the capacity of condenser No. 1, were chosen as units of observation. The formula for the maximum voltage then becomes

$$V = k\frac{E}{fC} \tag{2}$$

k being a constant of the apparatus and E the reading of the voltmeter. It was assumed, on the basis of information from the Bureau of Standards, that the capacity of the Moscicki condenser varies only a fraction of one per cent over the range of frequency investigated.

The Observations

It was possible in the three-hour period mentioned above, to make one or sometimes two sets of observations at 60 cycles, two sets in the neighborhood of 600 cycles and several sets between 1500 cycles and the maximum frequency obtainable, as limited by the rated speed of the machine or more often by the capacity of the direct-current instrument. Each set of readings consisted of from five to twelve observations of the corona voltage. As a general thing, repeated sets of observations agreed very closely, that is, within a few tenths of one per cent, but sometimes they would differ by as much as 2 per cent. These differences could not be accounted for. The constancy of the corona voltage was not always such that full advantage could be taken of the accuracy of the method, and apparent constancy of conditions. The following table is an

example of a set of readings in which the agreement was very good:

D-C. Instrument	Low-tens. voltage of trans.	Speed in rev. per min.
140.2	102.3	968
140.5	102.3	968
140.0	102.0	973
140.0	102.7	968
140.0	102.1	968
140.0	102.1	
139.5	102.1	969
139.3	101.5	
139.8	102.1	968

The following table is an example of a rather bad set:

D-C. Instrument	Low-tens. voltage of trans.	Speed in rev. per min.
89.0		1050
91.0	Off scale	1038
90.8		1038
91.0	*i. e.*, over 130 volts.	1038
90.3		1038
90.9		1038
91.9		1037

The results for the tube 4.58 cm. in diameter are given in Table I, and those for the 6.35-cm. tube are given in Table II. The voltages given were calculated by means of formula (**2**). These results are plotted in Figs. 3 and 4 respectively. In these figures the points of each set are connected by straight lines in order to make interpretation easier. Each point represents a series of from five to twelve observations.

Table III gives the values of effective high-tension voltages, ratio of transformation, and peak factor, that is, ratio of maximum to effective high-tension voltage, for various voltages and frequencies over the entire range explored. The maximum values are those observed with the condenser and mercury-arc rectifier apparatus as described. The peak factor at 60 cycles was about 1.48. The range of peak factors obtained in the course of the observations consequently is from 1.66 to 1.27. The wave of voltage, therefore, did not depart greatly from

TABLE 1

CORONA VOLTAGES FOR WIRES IN TUBE 4.58 CM. IN DIAMETER.

Diam. of wire	Series of observations	Frequency in cycles per second	Voltage / k
0.317 cm. (0.1249 in.)		59.0	1.242
		1338	1.191
		1680	1.202
0.234 cm. (0.0924 in.)	1	59.2	1.079
		558	1.061
		575	1.063
		1368	1.048
		1372	1.060
		1914	1.042
		1948	1.043
	2	58.5	1.081
		583	1.039
		1362	1.037
		1370	1.053
		1826	1.037
		1968	1.047
	3	58.0	1.076
		585	1.040
		1368	1.038
		1672	1.043
		1970	1.041
		2076	1.042
0.194 cm. (0.0763 in.) (tool steel)	1	59.5	0.998
		569	1.960
		2006	0.976
	2	58.8	0.999
		566	0.977
		567	0.973
		1336	0.986
		1884	0.982
	3	60.5	0.995
		590	0.950
		590	0.951
		1370	0.968
		1410	0.963
		1692	0.967
		2058	0.967
		2122	0.958
0.164 cm. (0.0644 in.)	1	59.6	0.904
		568	0.877
		576	0.893
		1376	0.895
		1418	0.888
		1754	0.885
		2176	0.884
		2412	0.880
	2	58.9	0.919
		587	0.882
		1378	0.886
		1396	0.886
		1730	0.878
		2110	0.880
		2372	0.875
	3	58.3	0.928
		584	0.880
		1368	0.885
		1674	0.894
		2054	0.890
0.106 cm. (0.0418 in.)	1	59.5	0.758
		573	0.738
		575	0.738
		2640	0.737
		2650	0.739
		2822	0.728
	2	59.1	0.748
		598	0.728
		598	0.729
		1416	0.716
		2134	0.725
		2908	0.700
		2966	0.700
0.089 cm. (0.0350 in.)	1	59.5	0.689
		60.0	0.683
		558	0.685
		570	0.680
		2822	0.656
	2	59.4	0.683
		573	0.683
		1406	0.680
		2792	0.677

the sine shape. The ratio of transformation of the transformer increased between 60 cycles and 2958 cycles by about 30 per cent.

TABLE II

CORONA VOLTAGES FOR WIRES IN TUBE 6.35 CM. IN DIAMETER.

Diam. of wire	Series of observations	Frequency in cycles per second	Voltage / k
0.317 cm. (0.1249 in.)	1	59.8	1.370
		578	1.313
		1294	1.338
		1622	1.313
	2	59.4	1.362
		274	1.402
		346	1.373
		423	1.361
		502	1.366
		566	1.360
		1298	1.350
		1440	1.350
		1638	1.336
0.234 cm. (0.0924 in.)	1	58.3	1.198
		585	1.147
		1360	1.148
		1684	1.161
	2	58.9	1.188
		284	1.223
		316	1.212
		354	1.191
		467	1.091
		529	1.166
		566	1.191
		570	1.181
		1098	1.166
		1460	1.170
		1848	1.151
	3	58.1	1.175
		58.6	1.191
		274	1.191
		342	1.197
		421	1.164
		469	1.122
		527	1.159
		570	1.174
		1392	1.174
0.164 cm. (0.0644 in.)	1	58.6	0.994
		585	0.955
		1372	0.961
		1740	0.952
		2102	0.959
	2a (without series inductance in low-tension circuit.)	272	1.031
		274	1.037
		347	1.031
		473	0.982
		528	1.016
		584	1.004
	2b (with series inductance in low-tension circuit.)	275	1.039
		346	1.019
		388	0.996
		423	0.982
		463	1.010
		528	1.011
		570	1.019
0.106 cm. (0.0418 in.)	1	58.7	0.796
		59.4	0.795
		594	0.765
		1388	0.776
		1766	0.770
		2134	0.775
		2644	0.761

DISCUSSION

Referring to Figs. 3 and 4, it will be noticed that there is a considerable amount of irregularity in the locations of the successive points with reference to smooth curves. This

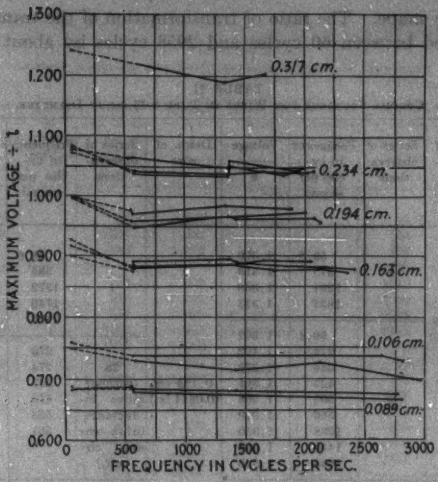

FIG. 3—CORONA VOLTAGES. TUBE 4.58 CM. IN DIAMETER.

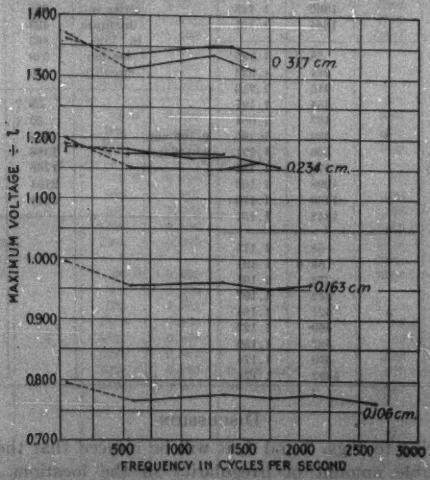

FIG. 4—CORONA VOLTAGES: TUBE 6.35 CM. IN DIAMETER.

result has been a surprise and a disappointment. Much care was taken to obtain the best conditions of accuracy in all of the instruments used. Further, during any one set of observations, there was never any indication of varying conditions. Consecutive readings taken in any one set of conditions repeated themselves accurately for the most part, and in altering the frequencies there was no suggestion, during the observations, of unstable conditions (except in one region, as described below). No cause could be found for the difference between the obser-

TABLE III

RATIO OF TRANSFORMATION AND PEAK FACTOR

Frequency in cycles per second	Low-tension voltage	Ratio of trans. R	Peak factor P	Frequency in cycles per second	Low-tension voltage	Ratio of trans. R	Peak factor P
58.4	90.6	1.000	1.000				
592	54.0	2×1.049	0.860	58.0	89.9	1.000	1.000
594	40.1	2×1.048	0.869	274	125.5	1.007	1.120
1382	62.0	1.033	0.920	274	115.5	1.007	1.120
1370	93.4	1.040	0.946	350	101.5	1.012	1.028
1732	92.6	1.074	0.920	344	130.0	1.017	1.078
2130	50.2	1.100	0.913	417	130	1.017	1.028
2112	73.2	1.131	0.921	427	53.0	0.991	1.037
2080	94.0	1.148	0.923	471	37.1	2×1.027	0.907
2392	46.5	1.189	0.912	458	65.8	2×1.011	0.888
2264	78.5	1.158	0.923	522	75.5	2×1.014	0.889
2958	44.9	1.310	0.908	526	51.5	2×1.031	0.885
				526	32.5	2×1.052	0.881
				558	74.5	2×1.038	0.894
				556	61.0	2×1.032	0.896
				560	46.9	2×1.021	0.896
				556	33.3	2×1.037	0.900

P = peak factor of 60 ~ generator = 1.48 approx.
R = ratio of transformation at 60 ~ = 125.1 : 1 or 250.2 : 1.

vations over the same range from one day to another. Temperature and pressure were eliminated as possible causes for these differences by successive series of observations under the same conditions, approximately, as to temperature and pressure.

There seems, however, to be no doubt that there is a decrease in the corona voltage, amounting to about 3 or 4 per cent, in increasing the frequency from 60 cycles to 2000 cycles or over. This decrease is apparently more pronounced for the larger sizes of wire.

It will be noticed that the points showing most serious departure from a regular curve are those for frequencies within the range 300 to 600 cycles. The observations in this range have caused much trouble, and for this reason the curves have been drawn in dotted lines, indicating uncertainty as to the observations. As nearly as could be determined, there was a tendency for the maximum corona voltage to take a sharp dip in passing through this range. There were, however, several accompanying conditions of experiment which may well account for the irregular results. For example, the connection of the high-tension winding of the transformer had to be altered in this range in order to make the necessary change in the corona voltage. Attention has already been drawn to the influence of this change on the charging current of the windings. It will be seen from Table III that there is evidence of a difference in the high-tension wave form for the series connection and the parallel connection of the two halves of the high-tension winding. Further, at about 425 cycles, and within a certain range of field excitation of the generator, there was a pronounced evidence of resonance in the high-tension circuit. On the smallest possible change in the field current of the generator, the reading of the d-c. instrument, indicating the maximum voltage, increased sharply from 35 to 80. Observations taken at this frequency on a larger wire and for values of voltage above the unstable region, showed no unusual conditions other than a slight irregularity of voltage which was readily damped out by series inductance in the low-tension circuit.

Still further evidence of abnormal conditions in the range from 300 to 600 cycles was found in the different results obtained in the series and parallel connections of the high-tension winding. Between 270 and 425 cycles, with the series connection, a spark would pass between wire and outer tube at a voltage only about ½ that required to produce corona when the high-tension winding was connected in parallel. The same phenomenon was observed in the range 450 to 600 cycles, with the exception that the parallel connection gave the spark at low voltage. This spark was intermittent, apparently localized, and very different from the usual uniform corona. The impression made was that there was a series of short impulses of abnormally high voltage.

While it is evident, therefore, that there were a number of abnormal conditions surrounding the observations in the region 300 to 600 cycles, there is no obvious reason why, if the conditions

were steady, the maximum value of voltage could not have been picked out by the mercury arc peak voltmeter. There is every indication that the mercury arc is instantaneous in action. Nevertheless, there seems to be no other conclusion than that the conditions of resonance described above, introduced very brief voltage impulses of high value which the mercury arc and condensers did not pick out. Considerable variation was obtained in the wave form by connecting the armatures of the two generators in series, thus obtaining a pronounced fifth harmonic. There was no resulting variation of the corona voltage; such variation, however, could hardly be expected unless the frequencies were far higher than 3000 cycles.

The corona from 1500 cycles upward appears also to differ qualitatively from that at lower frequencies. It is a common observation at 60 cycles that the gold-leaf of the electroscope descends in a jerky fashion when corona voltage is reached. The time taken for complete discharge is about 30 seconds. This has been attributed to the exact constancy of the corona voltage and the usual slight variation of the impressed voltage. From 300 to 600 cycles the electroscope discharged quickly but steadily, the time for discharge being one or two seconds. From 1500 to 3000 cycles the electroscope discharged in a very small fraction of a second, the gold-leaf descending practically instantaneously. There is absolutely no indication of leak before any of these observations.

A further interesting phenomenon at the higher frequencies was the vibration of the wire in the case of the open tube, when the points of suspension were some distance beyond the ends. At 1500 cycles the presence of corona caused the wire to vibrate greatly. There was no vibration before the appearance of the corona. The tension on the wire was altered through a wide range, but the vibration persisted unchanged. There is apparently, therefore, no connection between the frequency of the voltage and the natural period of vibration of the stretched wire. At 60 cycles the wire remained perfectly steady, even when surrounded by a strong corona. These vibrations, therefore, are apparently forced vibrations due to some property of the corona.

In considering the possible influence of the frequency on the appearance of corona in terms of the theory of secondary ionization or ionization by collision, there are three possible ways in which this influence might act: (1) The conditions of stable equilibrium

of the systems of vibrating electrons within the atom of the gas would be affected in different degrees by periodic electric forces of different frequencies. (2) With increasing frequencies, the time during which a single free moving electron is acted on by the electric force in one direction would be less; consequently the velocity acquired and energy available for ionization by collision would be less. (3) It has been suggested that the corona occurs when the density of ionization in the gas at the surface of the wire reaches a certain value. This increase in density results from the passage inward of electrons from a distance. As they move in they create more ions by collision. More ions are created on the inward path than are lost by recombination during the reverse half of the alternating cycle. At higher frequencies the rate at which the ions would reach the wire would probably be lowered, thus demanding a higher voltage for the appearance of corona.

Of these three possible methods of explanation the first two are apparently untenable, certainly for the range of frequencies investigated in these experiments, by reason of the fact that the periods of vibration within the atom and the time during which an electron passes from one collision to another, are infinitesimally small, compared with the time of reversal of the electric force at the frequencies investigated.

The experiments were carried out in the Physical Laboratory of the Johns Hopkins University. The authors wish to acknowledge the valuable assistance of Professor A. H. Pfund, in connection with the mercury lamps, and of Mr. M. W. Pullen at various times throughout the work.

Summary

The most important results of the work are as follows:

(1) The corona voltage at 2000 cycles is lower by 3 or 4 per cent than it is at 60 cycles.

(2) The corona in the range 300 to 3000 cycles has a number of qualitative differences from that at 60 cycles.

(3) Convenient methods for measuring high-tension maximum and effective voltages at frequencies up to 3000 cycles have been devised.

(4) An instance of resonance due to the capacity of the high-tension windings of a transformer is recorded.

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SPHERE GAP DISCHARGE VOLTAGES AT HIGH FREQUENCIES

BY J. CAMERON CLARK AND HARRIS J. RYAN

Abstract of Paper

The paper describes a series of experiments made by the authors to determine the values of steady high-frequency, high-voltage currents required to discharge between seven-inch copper spheres in air, at ordinary temperatures and barometric pressures. A 15-kw. arc generator was used as the source of high-frequency sustained high voltage, and the apparatus employed in securing and measuring currents of 123,000, 255,000 and 612,500 cycles is described in detail.

The sphere-gap standard consisted of electrolytic copper spheres mounted on the ends of brass tubes in treated wooden frames, and the gap lengths were accurately determined by means of calipers and micrometer screw or steel scale.

The results obtained are given in Tables II and III and are also charted in curves I and II, Fig. 5. The 123,000-cycle values show a right-line relation between sphere gaps and discharge voltage, which line, when extended, passes through the origin. The high-frequency voltages are almost uniformly 4.5 kv. below the 25-cycle voltages observed by Chubb and Fortescue.

Introduction

THE predatory character of high-frequency currents due to accidental causes on transmission lines is now generally recognized, especially with reference to insulation. The modern high-power radiotelegraph has encountered occasional difficulty in the maintenance of insulation that is also stressed with high-frequency high voltage. These facts have emphasized the need of more quantitative knowledge of high-frequency phenomena. To obtain this knowledge many laboratory studies and measurements will have to be made to provide more conclusive data and trained mental equipments required to interpret causes of insulation failure and to eliminate them.

To aid in these matters we have undertaken to determine the values of steady high-frequency high voltages required to discharge between seven-inch (17.7-cm.) copper spheres, in air, at ordinary temperatures and barometric pressures.

High-Frequency Sustained High-Voltage Source

A 15-kw. Poulsen-Federal arc generator was used. See Fig. 1. The arc is drawn in a powerful magnetic field and surrounded by water-cooled illuminating gas. A slowly-rotating carbon rod forms the cathode, and a water-cooled bronze lug forms the anode. The characteristics of this particular arc have not as yet been fully determined. At 17.6 amperes direct current through the arc and 12.5 amperes alternating current at 123,000 cycles per second in the oscillating circuit, the arc is stable at 1200 continuous volts. Under these conditions the resistance ballast at *R* is all cut out, and the power

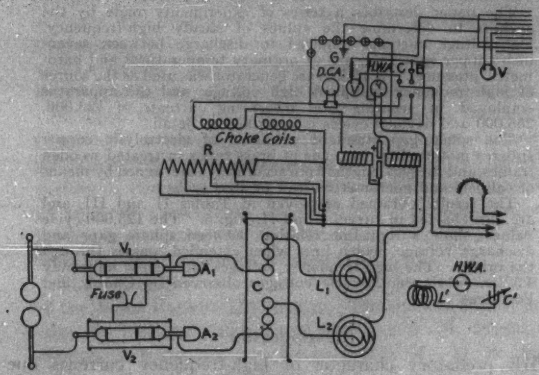

Fig. 1

consumed in the oscillating circuit is chiefly that lost in the carborundum safety resistance rods, *SR*, in series with the sphere gap. This power amounts to about one kw. There are two of these rods, each $8\frac{3}{4}$ in. (222.25 mm.) long and $\frac{3}{4}$ in. (19.05 mm.) in diameter. The charging current taken by the seven-inch (17.7-cm.) spheres at 123,000 cycles is sufficient to maintain the rods at a bright cherry-red temperature.

The insulation of the field coils of the arc generator must be extra heavy, as the duty put upon it is severe. The outer terminals of the coils are connected to the anode and cathode of the arc. Correspondingly, the inner terminals are connected to the inductances that protect the direct-current generator

from "static". Adjustable static arrester gaps shunt these field coils to short-circuit the "kick" of the field when the arc breaks. The arc will break occasionally, stopping the current through the field coils with suddenness. The discharge from these field coils will puncture their own insulation and that of the direct-current generators if such inductances and dischargers are not used. For greater safety in this regard, a series of carbon-filament incandescent lamps connects across the terminals of the generator. The middle of the series is grounded. Two 7.5-kw., 600-volt direct-current generators furnish current to the arc-generator. They are connected in series, with their mid-connection grounded. The first machine is separately excited from a 125-volt source. The 600-volt field of the second generator is excited with current taken from the armature of the first generator. Thus a rheostat in the field of the first generator controls the total direct-current supply voltage. This rheostat is mounted so that one can conveniently use it to adjust the direct-current supply voltage when he is starting the arc generator or adjusting its action.

The arc generator equipment includes one 50-ampere, direct-current ammeter showing the average direct current drawn from the continuous-current supply generators; one 30-ampere Hartmann and Braun "hot-band" ammeter measuring the high-frequency amperes circulating in the oscillating circuit; one voltmeter for reading the continuous-current supply voltage; and a high-frequency voltage gage connected across the arc to enable one to know the voltage duty demanded of the arc to set up a given current in the oscillating circuit. The last instrument is easily made by connecting a one-ampere hot-wire ammeter in series with two pairs of common tin sheets at ½ in. (12.7 mm.) separation, functioning as a condenser, and connected across the arc. The charging current taken by such a condenser, as indicated by the hot-wire ammeter, is roughly proportional to the high-frequency voltage duty demanded of the arc. Such voltage is decidedly of irregular wave form, so that this instrument functions simply as a *voltage gage*.

The inductance in the oscillating circuit is made up of approximately 2000 ft. (609.6 m.) of ¼-in. (6.3-mm.) soft copper tubing, forming six helices of 25 turns each. Each helix is mounted on six hard-rubber rods. The helices have graded diameters so that they may be telescoped to form one six-helix inductance or a pair of inductances of three helices each. The

travel of the turns is the same for all helices,—an important matter when these large inductances are to be formed by telescoping. When the travels are not the same, *i.e.*, when they reverse from layer to layer as in the ordinary solenoid, the distributed capacity of the inductance is broken into chunks, causing turbulent interference with the growth of the oscillating current. In a nest of helices the circuit leads through the first from the bottom turn to the top turn, thence downward to the bottom turn of the next helix, then out at the top, and again in at the bottom of the next, and so on through the whole set. Oscillating currents are easily driven through inductances of this sort when connected in series with suitable condensers. Even with this favorable construction the helices may not be nested in a single set because the duty demanded of the arc will easily exceed its voltage capacity before a fair value of high-frequency current has been set up. It is necessary to mount the helices in two sets, preferably of equal inductances. Then, when a single condenser is connected symmetrically between the two inductances, and in series therewith, the phase displacements that the oscillating currents encounter with respect to the arc are opposed and balanced. The high-frequency voltage duty demanded of the arc is correspondingly light. Without resorting to delicate balancing, 50,000 volts and 12.5 amperes at a frequency of 123,000 cycles per second may be developed in this apparatus. With greater care in balancing than we have so far employed, higher oscillating voltages can doubtless be developed.

The main condenser in the oscillating circuit is made up as shown at *C* in the diagram of the complete outfit given in Fig. 1. Each electrode is formed of cylinders of galvanized sheet iron seven ft. (2.1 m.) long and five in. (127 mm.) in diameter, equipped with hemispherical ends. They are also equipped with hooks and eyes so that chains of parallel cylinders may thus be formed. The capacity can be increased or decreased by attaching and detaching one or more of these cylinders from each of the two electrode chains. This feature enables the capacity in the oscillating circuit, and therefore the frequency, to be varied over wide limits. At present this main condenser is equipped with a chain of four cylinders at each electrode. The chains hang in a vertical plane between a pair of neutral plates forming a hood about the capacity cylinders, as shown in Fig. 1. The frames of these plates are made of common

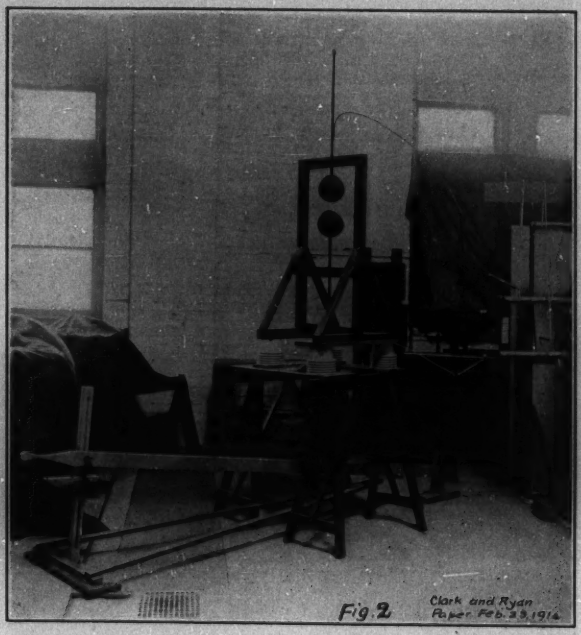

FIG. 2

FIG. 3

FIG. 4

galvanized iron pipe, $\frac{3}{4}$ in. (19.05 mm.) internal diameter; the bodies of the plates are constructed of galvanized iron, 23-mil sheets. The plates are tied together with a conductor. They are insulated from ground for a small portion of the total oscillating voltage, for unless special care is taken there is some unbalancing that sets up a potential between the plates and ground. The illustrations, Figs. 2, 3 and 4, give an idea of the actual manner in which the above parts of the generating equipment are formed and arranged. To the capacity of the main condenser there is necessarily added the capacity of the concentric-cylinder voltmeter condenser, V_1 V_2, to be considered later.

In the final stage of the present undertaking, the number of helices was doubled by placing the six copper tubular helices in one nest and by the addition of a set of six helices of the same size, in which the conductor used is a "flat magnet wire" 0.34 by 0.04 in. (8.6 by 1 mm.) in section. The latter set was made up, primarily, to serve as a protective inductance at the main terminal of a low-frequency high-voltage series of transformers, the other main terminal being grounded. However, by giving the helices of this set proper dimensions they could be used along with the regular set for the generation and measurement of higher voltages at lower frequencies in the standardization of the sphere-gap voltmeter. When using the largest capacity and self-induction that the equipment thus provides, 12.5 amperes at 100,000 volts and 85,000 cycles per second are produced in the oscillating circuit. Correspondingly, when the capacity is reduced to the lowest practicable limit, viz., that of the voltmeter condenser, and the self-induction is limited to that of the pair of small innermost helices, 8.1 amperes and 13,000 volts at 612,500 cycles are produced.

The carborundum protective resistance in series with the sphere-gap voltmeter could not be used at frequencies much above 123,000 cycles. This is due to the magnitude of the charging currents inevitably taken by the spheres and their connections, which cause excessive losses in resistances proportioned so as to limit properly the 1200-volt direct power-current that follows a discharge across the gap. At higher frequencies a fine-wire fuse, guarded to prevent corona, was used to limit the injury produced by the power currents. The capacity of the fuse must necessarily be large enough to carry the charging currents taken by the spheres and their connections. On

this account such fuse capacity cannot be made small enough entirely to prevent injury to the spheres. To overcome this difficulty in the later stages of the work, when frequencies higher than 123,000 cycles were used, the Fortescue-Chubb-Farnsworth mounting for the spheres had to be slightly modified. The brass rods supporting the seven-in. (17.7-cm.) spheres were terminated in shallow cups with inside surfaces fitting them. The spheres were then mounted upon these cups, being held in place by thin sheet brass halters and rubber bands. These changes in the sphere gap standard do not appear to be of material consequence as affecting its integrity for the present class of measurements, while they permit the spheres to be rotated when their adjacent surfaces have been injured so as to bring into use new and uninjured surfaces. By this means the reliable useful life of the spheres is prolonged to such an extent that their renewal cost becomes nominal.

High-Frequency Meter

In the present undertaking a reliable frequency or wave meter is of prime importance. The frequency meter employed was made by connecting an inductance standard in series with a variable condenser of reliable make and of a type commonly employed in radio work. Three entirely independent methods were employed for standardizing this meter.

I. *By Calculation*: In this method the value of the inductance was calculated. The conductor used in its construction was enamel-insulated litzen draht, silk-jacketed. When constructed, the dimensions were obtained with some care. Perry's formula[1] and Doggett's method[2] were used to calculate independent values of the inductance. The results obtained were 879.0 and 882.5 microhenrys. The variable condenser was compared with a standardized condenser of the Federal Telegraph Company. It was also compared with an air-core standard formed of two concentric brass tubes. The scale of the condenser was found to be true and linear. Its total capacity at the 180-deg. setting compared with the Federal standard was found to be 0.00405 microfarad and with the brass tube standard 0.00407 microfarad.

1. Perry's Approximate Self-Inductance Formula. *Bulletin*, Bureau of Standards. Vol. 8, No. 1, p. 136. Jan. 1, 1912.

2. Leonard A. Doggett. The Inductance of Air-Cored Solenoids. *Electrical World*, Vol. 63, p. 259, January 31, 1914.

II. *By Direct Measurement, as follows*: At a definite setting of the wave meter the current through and the voltage across the terminals of the meter condenser were read. A one-ampere Hartmann and Braun hot-band ammeter was used for the current and a Kelvin multicellular electrostatic voltmeter for the voltage. The latter instrument is essentially an air-core condenser. Its capacity could be determined conveniently and accurately by noting the change in the frequency meter reading that was caused by its presence. An exact correction on its account could therefore be made. The frequency was then calculated from the simple and well-known relation of voltage, current and capacity. This value was found to be 123,000 cycles to check with 122,500 cycles obtained by method I.

III. The wave meter was then taken to the factory of the Federal Telegraph Company in Palo Alto. There, through the courtesy of Mr. Ralph Beal, it was compared with the wave meter that had been standardized by the Bureau of Standards. The two wave meters were found to be in close agreement, differing only by ¼ per cent.

For higher frequencies the wave meter was recalibrated by method II to eliminate errors that appear due to the internal capacity of the wave meter inductance.

High-Frequency High-Voltage Meters

The high voltages generated in the main condenser, C, Fig. 1, of the oscillating circuit, contain pure sine waves of a single frequency only. The rough pulsating voltages of the generator arc are completely absorbed by the main inductances, $L_1 L_2$, in the oscillating circuit. A reliable voltage meter was, therefore, made out of a suitable condenser of known capacity connected in series with a hot-band ammeter that is free of frequency effects.

For balancing purposes and to employ convenient dimensions in other respects, it was found best in the present work to make up and use two of these condenser-type voltage meters. The manner of their construction is shown at $V_1 V_2$ in Fig. 1. They were made in principle the same as that used by Chubb and Fortescue in standardizing the Farnsworth-Fortescue sphere gap voltmeter.[3] Each condenser was made concentric and near to these specified dimensions: Outer cylinder: inner diameter 11.0 in. (27.9 cm.) length 72 in. (1.8 m.). Inner cylinder: outer diameter 7.0 in. (17.7 cm.), gross length, not including wood-

3. L. W. Chubb and C. Fortescue, Trans. A.I.E.E., Vol. XXXII, 1913, p. 739.

mounted hemispherical tinfoil-covered end caps, 61.0 in. (1.54 m.). Two central sections effective for use; one, length 12 in. (30.4 cm.), the other 24 in. (60.9 cm.); total when connected in multiple 36 in. (91.4 cm.). These cylinders were constructed of 23-mil galvanized iron. The inner cylinders were carried on a nine-ft. (2.7-m.) length of common 1 3/4-in. (3.44-cm.) galvanized iron pipe. The outer cylinders were mounted one over the other, in an A-frame of wood, insulated on porcelain cleats from the cement floor against the small differential voltage; the inner cylinders were supported in position by sash cords. This support was made adjustable for centering by wedges. Errors due to eccentricity were measured and found to be negligible by noting changes in charging currents indicated by a synchronous commutator and portable direct-current galvanometer. The high-frequency high voltages were applied to the inner cylinders by connecting to the pipe ends remote from the arc-generator. On the pipe ends facing the main inductances and the arc-generator, metal guard hoods were attached, A_1A_2. In them, five-ampere or one-ampere hot-band ammeters were mounted and connected in series with the pipe and the central insulated condenser sections, so as to measure the charging current taken by such sections. The fronts of the hoods were made hemispherical of fine wire mesh to admit light. Through these, openings were cut to facilitate reading the ammeters from a distance by means of telescopes. An observer going near enough to read these instruments with the unaided eye would greatly disturb the balance of the oscillating system, cutting down the high-frequency voltage sometimes by as much as 50 per cent, through the increased duty demanded of the arc when circulating current in an unbalanced circuit. Since the capacity values of the used sections of these condensers are made definite in terms of their linear dimensions by means of the guard ends, calculation was relied upon entirely to determine such values. In the upper cylinder the total capacity of the 36 in. (91.4 cm.) of used section was found to be 0.0001140 microfarad, and correspondingly, for the lower cylinder 0.0001145 microfarad. In obtaining the results herein reported, a five-ampere ammeter was used in series with the 0.0001145 microfarad in the lower cylinder and a one-ampere ammeter in series with one-third of the aggregate 0.0001140 microfarad available in the upper cylinder.

For safety, the outer upper and lower cylinders, which operate nearly at ground potential, are connected to the electrodes of a

horn-gap bridged with a long fine-wire fuse. Occasionally, when the arc was about to break, an unbalancing surge would produce an extra high voltage that would discharge across the double two-in. (50.8-mm.) gaps between the voltmeter cylinders. If such discharge should strike the section of the inner cylinder that is connected through an ammeter it might be burned out before the fuse would interrupt the resulting short circuit. To prevent this, aluminum rings made from 1/4-in. (6.3-mm.) rod were fitted over the extreme ends of the inner cylinders. The discharges then took place from these rings, removing the danger from injury to the hot-band ammeters by short circuits. See Fig. 1. To lessen the spread of the electrical field set up from the hoods covering the ammeters, a sheet metal screen was mounted near them. This screen, the outer cylinders and the large hood over the cylinders, forming the main oscillating-circuit condenser, were all connected and operated near zero potential.

Stability in the production of high voltages by resonance from an arc-generator as a source, depends upon the constants of the oscillating circuit. These must be so established and related that oscillations can be set up at a single frequency only. In the equipment herein specified this condition could not be fully realized without encountering too much cost. The use of a single main condenser in series with two magnetically coupled inductances in the oscillating circuit fixed the frequency and gave ample stability. When the two concentric voltmeter condensers were added to the main condenser, it was found that the voltage duty put upon the arc-generator was somewhat increased. The oscillating freedom of the circuit was correspondingly impaired. This was no cause of difficulty in measuring voltages up to 50,000. Above 50,000 volts one or the other of the concentric voltmeter condensers was apt to flash over, due to a tendency of the complex circuit to start local damped oscillations at much higher frequencies. The condenser voltmeter could not be used, therefore, to measure voltages much beyond 50,000.

The Sphere-Gap Standard

Electrolytic copper spheres were used and mounted on the ends of brass tubes in treated wood frames with proportional dimensions exactly as specified by Farnsworth and Fortescue.[4] Satisfactory spheres may be obtained at small cost by selecting

4. S. W. Farnsworth & C. L. Fortescue, Trans. A.I.E.E., Vol. XXXII, 1913, p. 733.

them for regularity of surface curvature from the commercial float ball product. Well-impregnated paraffined oak was used for the cross pieces through which the brass tubes pass to support the spheres. The rest of the frame was made of Oregon pine. Under the stress of high-frequency high voltage all dielectrics accept large charging currents. Ample and close electrode contact, entirely free of all corona, must be made, to lead these charging currents into the stressed dielectric so as to prevent burning or other injury. Accordingly the holes through the oak cross pieces were bushed with brass sleeves cemented to the wood by paraffin treatment. Without this precaution the frame will promptly be set afire. For balancing purposes we had to set this sphere gap standard rather high off the floor. For reasons given above, it could not be operated with one terminal grounded as recommended by Fortescue, Chubb and Farnsworth. We also used a long wooden lever and screw jack to facilitate accurate gap settings. Gap lengths were determined by means of calipers and micrometer screw or steel scale.

Finally, reference is made to the three illustrations Figs. 2, 3 and 4, which give to the eye much additional information relating to the construction and arrangement of the equipment as employed and above described.

Features of Unsteadiness in the High-Frequency High Voltages Generated in the Apparatus as Used and Described Above

The character of the high-frequency voltages was examined with the aid of the cathode ray cyclograph. The ray was given an alternating deflection in one plane magnetically, and in a quadrature plane, electrostatically. The magnet deflections were produced by the oscillating currents. Limitations in the behavior of the cathode ray tube made it necessary to use an air-core transformer in series with the oscillating circuit. The secondary of this transformer was short-circuited through the current coils of the cyclograph and grounded. Thus the cathode ray was not subjected to the potential disturbances that occur when the deflecting coils are directly connected in series with the oscillating circuit adjacent to an ungrounded electrode of the generator-arc.

The ray was deflected electrostatically by "quadrants" charged with the potentials of spherical electrodes that were

dipped into the powerful electrostatic field of the main condenser. The two alternating motions thus imparted to the ray being in quadrature, it was made to trace an ellipse on the observing screen of the tube. One could then note the characteristic manner in which the magnitude of the high-frequency voltage varied. The lowest current that could ordinarily be maintained in the oscillating circuit at 123,000 cycles was 3.0 and the highest 12.5 amperes, corresponding to 12.0 and 50.0 kilovolts respectively. The cyclograph indicated unsteady voltage fluctuations amounting to a maximum of 15 per cent, approximately, at 3.0 oscillating amperes. As the oscillating amperes increased, the instantaneous voltage became quite steady, fluctuating less than 5 per cent, maximum. As the current approached 6.0 amperes, producing 24.0 kilovolts, the voltage became quite unsteady. It was always difficult to operate the arc-generator at 6.5 amperes. At such current the hot-band ammeter reading fluctuates and the cyclograph indicates violent fluctuations in the oscillating current and voltage. Persistence of vision frequently caused two concentric cyclograms to appear upon the screen, one corresponding to a current of about six, and the other, seven amperes. Because of this characteristic of the arc no attempt at any time was made to determine sphere-gap discharge voltages at or near 6.5 amperes, corresponding to 26.0 kilovolts. At seven amperes and upward to 12.5 amperes, the cyclograph again indicated steady instantaneous oscillating voltage, whenever the hot-band ammeter in the oscillating circuit produced steady readings.

In making sphere-gap voltage discharge observations the arc-generator was operated and controlled so as to establish a definite high-frequency current in the oscillating circuit. While the sphere gap was shortened slowly to produce the discharge, the ammeters in the main oscillating and voltmeter condenser circuits were read. A set of observations was considered good only when the ammeters gave steady indications. In general, however, under the most steady operating conditions there are some slight and rather rapid fluctuations in the values of the current and, therefore, voltage. The ammeters can only indicate the effective average of such currents and voltages. On the other hand, it is the effective maximums of the slightly fluctuating voltages that actually produce most of the discharges between the spheres. In this manner variable errors are produced in the results, and some strategy is necessary to accomplish

their approximate elimination. These errors always operate to produce apparent voltage values that are smaller than their corresponding true values. For obvious reasons the sphere gap can be shortened only at a slow rate. If it could be shortened at a very high rate and the process stopped at the exact length through which the discharge occurred, all settings would have nearly equal weight in determining the final true result. Under the actual working conditions in this equipment, it is hardly likely that the observed voltages are ever above the true voltages that actually produce the discharge between the spheres. Occasionally, however, the readings of the instruments must correspond much more nearly to the voltages applied to the spheres at the instant they discharge. *The corresponding results will be least in error and must have most weight in determining the final and true relation between voltages and spark gap lengths.*

TABLE I
TYPICAL OBSERVATIONS

Temp. 18 deg. cent. (approx.)				Barometer 30 in. (approx).		
Date	H-B 5-amp. No. 439188 constant multiplier 1.03 0.0001145 m. f.	H-B 1-amp. No. 429926 constant multiplier 1.02 0.0000380 m. f.	H-B 30-amp No. 439113 in main oscillating circuit	Degrees variable capacity (frequency meter180°)= 0.00406 mf. Inductance = 881. micro-henrys	7-in. sphere gaps, inches	Arc voltages gage
1914						
Feb. 5	1.45	0.460	7.90	84.60	0.695	
" 5	——	——	8.00	"	0. 93	——
" 14	1.43	0.456	8.00	"	——	——
" 14	1.50	0.474	8.45	"	——	——
" 14	——	——	9.00	84.5	0.801	48.
" 14	——	——	9.10	"	0.821	42.
" 14	——	——	9.10	"	0.820	43.
" 19	1.95	0.630	11.20	85.3	1.04	40.
" 19	2.08	0.670	11.80	"	1.03	——
" 19	2.13	0.690	12.20	84.5	1.06	42.

DISCUSSION OF RESULTS

Some of the original observations are given in Table I. The constants of the measuring instruments are also given, so that one may compute the corresponding results for himself. The results obtained are given in Tables II and III and charted

TABLE II
RESULTS

Frequency	7-inch sphere gaps; inches	Kilovolts by instruments
123,000	0.427	20.2
"	0.429	19.8
"	0.452	20.0
"	0.540	24.7
"	0.673	33.0
"	0.693	33.0
"	0.695	32.7
"	0.704	33.0
"	0.738	32.7
"	0.784	35.7
"	0.800	35.8
"	0.811	36.6
"	0.820	37.0
"	0.821	37.0
"	0.863	40.7
"	0.878	40.7
"	1.03	47.5
"	1.04	44.7
"	1.06	48.8
"	1.06	48.0
"	1.09	49.8
"	1.09	49.4
"	1.10	48.5
"	1.10	50.4
"	1.16	51.8

TABLE III
RESULTS

Frequency	7-inch sphere gaps; inches	Kilovolts, by instruments
255,000	0.261	13.500
"	0.253	13.300
"	0.248	13.250
"	0.371	19.060
"	0.378	18.460
"	0.382	18.400
"	0.337	17.670
"	0.404	20.770
"	0.898	43.300
"	0.817	42.600
"	0.886	42.200
"	0.920	42.300
"	0.901	41.900
"	0.931	43.700
"	0.934	44.200
612,500	0.320	14.950
"	0.263	12.300
"	0.285	13.200
"	0.242	12.480
"	0.250	12.200

in Fig. 5. It is noted that the 123,000-cycle values, when the fluctuating character of the source is ignored, locate a right-line relation for the sphere gaps and discharge voltages, and that such line when extended passes through the origin. See curve I, Fig. 5. All values determined at 123,000, 255,000 and 612,500 cycles locate curve II, Fig. 5, when errors due to the fluctuation of the source are largely eliminated.

Curve III, Fig. 5, was drawn for comparison; it was located

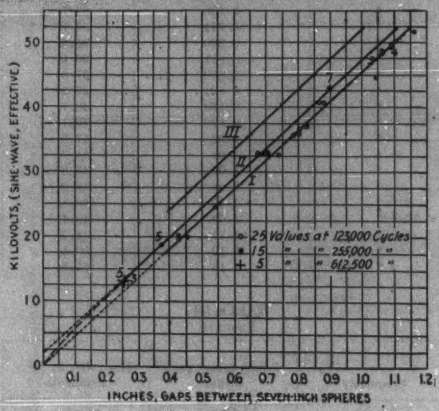

FIG. 5

I. Seven-inch sphere-gap discharge voltage at 123,000 cycles, fluctuations of source ignored. 25 determinations.

II. Ditto. 25 determinations at 123,000 cycles, 15 determinations at 255,000 cycles and 5 determinations at 612,500 cycles. Fluctuations of source eliminated by giving maximum weight to minimum gaps for corresponding voltages.

III. 25-, 37.5- and 50-centimeter sphere-gap discharge voltages at 25 cycles determined by Chubb and Fortescue, Proc. A. I. E. E., Feb. 1913, pp. 635-6.

with the observations made by Chubb and Fortescue for 25 cycles discharge voltages and 25-, 37.5- and 50-cm. sphere gaps. These observations are recorded on pp. 745-6 of TRANS. A. I. E. E., Vol. XXXII, 1913. The high-frequency voltages are almost uniformly 4.5 kilovolts below the 25-cycle voltages. No cause for this difference could be found in our methods of measurements. We believe that both curves have been correctly located.

Conclusions

1. The seven-in. (17.7-cm.) sphere-gap discharge voltages at frequencies ranging from 123,000 to 255,000 cycles per second are given by the expression

$$e = 45.5\, l + 2$$

for the gap range of 0.4 to 1.1 in. (1 to 25.6 mm.), wherein the value of e is in kilovolts, r.m.s., and the value of the sphere gap, l, is in inches at ordinary atmospheric conditions: Temp. 18 deg. cent.; barom. 30 in.

2. Correspondingly at 612,500 cycles per second, 13.06 kilovolts, r.m.s., discharge through a seven-in. sphere-gap length of 0.252 inch.

3. Needle gaps are not practicable for the determination of high-frequency high voltages. The points are promptly melted and burned. Only gaps between blunt points can be employed. For these, No. 14 B. & S. gage, square-ended copper wires were used. The measured voltages were found to be about one-half of the corresponding voltages at 60 cycles.

Acknowledgements

The writers could not have undertaken the present work without special equipment, provided as follows:

Mr. Cyril F. Elwell presented the Department of Electrical Engineering, Leland Stanford Junior University, with a five-kilowatt Poulsen arc oscillating-current generator. Later on the Federal Telegraph Company generously exchanged this generator for a powerful 12-kw. Poulsen-Federal arc-generator, together with a variable condenser and special minor supplies such as litzen draht, carbons and bushings. Invaluable advice and suggestions were rendered in the earlier stages of the work by Mr. Elwell and Mr. Leonard F. Fuller.

DISCUSSION ON "THE SPHERE GAP AS A MEANS OF MEASURING HIGH VOLTAGE" (PEEK), "THE ELECTRIC STRENGTH OF AIR—V, THE INFLUENCE OF FREQUENCY" (WHITEHEAD AND GORTON), AND "SPHERE GAP DISCHARGE VOLTAGES AT HIGH FREQUENCIES" (CLARK AND RYAN), DETROIT, MICH., JUNE 24, 1914.

L. W. Chubb: These three papers presented under the auspices of the Electrophysics Committee are very interesting, and they add a gread deal to our knowledge of high-voltage phenomena.

The paper on the sphere gap by Mr. Peek adds some valuable experimental data on the effect of barometric pressure on the gap voltages. The effect of temperature, however, as expressed in the empirical formula, seems to be a matter of assumption based on free-path and pressure, but not confirmed by experimental data. The inverse proportionality between breakdown voltage and absolute temperature may hold throughout the range of atmospheric temperatures, but the stream of negative electrons from hot metallic electrodes will possibly have a greater effect at high temperatures.

The theories of corona formation and breakdown voltage so far advanced can hardly be adopted as laws until they are more thoroughly tested out, between wider limits.

The formulas given by Mr. Peek agree well with his experimental results, as high as 320,000 volts. Our own direct calibrations with the 25-cm. and 50-cm. spheres agree very well as high as 320,000 volts, with the 50-cm. spheres (one grounded), but above this point the formula and the calculated values given in Table IV do not check with experimental data. For instance, for the grounded case a value in Table IV gives for a separation of 50 cm. a breakdown voltage of 541,000 volts. Direct calibrations show 478,000 when the insulated sphere is freely suspended from a crane and 458,000 volts when both spheres are mounted in the standard frame proposed by Messrs. Farnsworth and Fortescue. The last value given for non-grounded spheres shows a separation of 75 cm. at 725,000 volts. Our direct calibrations show a separation of just twice this gap at the same voltage and without visible corona on the spheres. Below 320,000 volts the points can be reproduced easily, they check the values given in the paper and the sphere gap seems to be a reliable standard for measuring maximum voltage. Above 320,000 volts the gap is unsteady, the strength of the gap is apparently much lowered, extraneous bodies have a greater influence and barometric pressure seems to have a much greater effect than is indicated by the formula. Tests have been made, with one sphere grounded, to voltages over 600,000, and with both spheres insulated, to over 900,000 volts. In the tests there was an increasing discrepancy with voltage increase, between the curves given in the paper and direct calibrations.

At high voltages there is a time effect of breakdown voltage.

Thus at a gap setting of 10 cm. the voltage was quickly raised and the gap broke at 188,000 volts. The gap was then increased one per cent and the same voltage broke over after an application of 55 sec. A second test showed a lapse of 40 sec. The gap was again increased one per cent, and it required 160 sec. for the same voltage to cause a breakdown. Similar effects were shown at other voltages above and below 188,000. At 100,000 volts the effect is inappreciable and below 95,000 volts no time effect could be noticed.

The effect of light is also being investigated and seems to play an important part between terminals which break above the corona point, but, within the range of working voltages, light of ordinary wave lengths has very little effect on the calibration of the sphere gap.

It was thought that the presence of so much corona in the neighborhood of the sphere gap during high-voltage tests might lower the breakdown voltage between spheres. Tests were made blowing air upon the gap from the side opposite to the high-tension apparatus. This air was drawn in a large wooden flume about 20 meters (65 ft.) from the gap and forced with a low-pressure blower across the gap. It was found that the air blast, instead of making the breakdown voltages higher and more consistent as expected, made the behavior more erratic, and caused premature static flash-overs across a gap 25 or 50 per cent greater than the separation required for final breakdown. Several explanations have been put forth to cover this effect, but they need not be mentioned at this time.

The precautions against oscillation given by Mr. Peek are very important, and the damping resistance both in the primary circuit and in series with the gap is very necessary.

The paper by Messrs. Whitehead and Gorton is certainly an example of a good record of the work done. After reading such a paper, one feels that he has no questions to ask why, how or under what conditions the several steps were followed out.

The vibration of the wire at high frequencies seems to prove that the wire was well centered. A stroboscopic view of the vibrating wire would probably show the wire to be vibrating at its natural period with an increased corona on the side of the wire in the direction of the instantaneous deflection. This corona causes the familiar electric wind, the reaction of which tends to restore the wire to the center. A possible explanation is that due to the lag of corona formation upon the deflection of the wire there is a greater force acting on the wire when it is traveling toward the center than when it is traveling outward, which would cause a sustained vibration.

The three possible explanations for the effect of frequency on corona formation, given on the last two pages of the paper, seem to indicate that at high frequency the appearance of corona would be at an increased voltage, while the results show the reverse effect.

All the papers show discharge at a lower voltage at high frequency, and the authors are certainly to be congratulated on this agreement. The discussion over a year ago which probably stimulated the frequency tests, contains several statements that the gap would be stronger at high frequency. The new records show clearly that direct tests rather than theories should be used to study such complex phenomena.

F. C. Caldwell: Would there be any chance for error due to the drop in the high series resistance, especially at high frequencies, or would the fact that the charging current is out of phase eliminate any such error?

D. M. Mahood: Referring to curves of Fig. 5, in the paper by Messrs. Clark and Ryan, showing discharge voltage for high frequency as almost uniformly 4.5 kilovolts below the 25-cycle voltages, it is suggested that this is due to the fact that pure undamped waves were not obtained during these observations. With about 10 to 15 ohms high-frequency resistance for the inductances L_1 and L_2 in the oscillating circuit, about 8 ohms high-frequency resistance for the carborundum safety resistance rods in series with the sphere gap, and about 2 ohms operating resistance of the arc itself, there exists a decrement of apparently 0.02. The cyclograph used, indicating only the r.m.s. value of potential existing, permits the periodic high swinging potential which breaks down the gap to slip by without being taken into consideration during observations.

The conditions existing during tests indicated in the first paragraph of the second page of the paper, showing 17.6 amperes direct current about equal to alternating current (12.5 r.m.s. or 17.6 maximum value) in the arc, are extremely unstable. Our experience with Poulsen arcs has shown that where such conditions exist there is considerable fluctuation of voltage and other conditions of the arc. With this maximum voltage value jumping up at times and not possible of indication on any of the instruments used, the discrepancy between the 25-cycle and high-frequency curves may result.

The best oscillating arcs constructed and specially designed for stability for measuring purposes (those of Lindemann, duplicating those of the German Reichsanstalt,) gave 2 per cent variation in amplitude at 133,000 cycles. Methods for standardized calibration making use of the oscillating arc are capable of too much error, caused by the instability combined with the occasionally swinging high-amplitude wave, and should not be considered conclusive until an opportunity is afforded to check the high-frequency results under more stable conditions, using high-frequency generator with absolutely constant speed maintained.

Charles Fortescue: Discussing first Mr. Peek's paper, the results of the tests under various atmospheric conditions, pressure, frequency, etc., are a valuable addition to our knowledge of the subject. It is gratifying to find that these tests

agree with theoretical figures, as far as they have been carried out. Mr. Peek's tables of spark-over voltages add nothing to the data already available on the subject, except in confirmation of the results obtained for 25-cm. spheres, with smaller spheres. On the contrary, Mr. Peek's assumption of constant apparent potential gradient at spark-over, for a given sphere, based on his assumption that this quantity is the same function of $\frac{x}{r}$ as the true intensity, leads to no useful result, and in my opinion beclouds the real issue. We are confronted with two problems: first, the calibration of sphere spark gaps of various sizes; second, determination of the theory of the voltage breakdown of the spark gap.

The old theory propounded by Russell has been found not satisfactory. Mr. Peek has evolved a theory of the effect of shanks. I do not think that the discrepancy can be attributed to the shanks. The shanks have very little effect on the breakdown voltage. I think it must be due to some other cause, and in attributing it to the effects of shanks, we are losing sight of the real issue and preventing ourselves from finding out the real reason of the discrepancy.

We have been working on the calibration of the spark gap in Pittsburgh, and as Mr. Chubb states, we have carried calibrations on a grounded 50-cm. spark gap from potentials of 300,000 volts up to 600,000 and above. In making measurements of the maximum value, we use the condenser terminal as a condenser. The condenser terminal is an excellent condenser. We judge from our experiments that the effect of the external bodies on the capacity can be made extremely small.

In our measurements there was no corona present on the terminal itself, under any of the measurements, except on the small choke coil on the top of the terminal. The wire leading to the spark gap had considerable corona, a soft glow without streamers. There was a certain amount of corona on the resistance leading to the spark gap and on the bushing through which the shank of the spark gap passed. It may be that in making our measurements by means of this condenser, and averaging the value of the charging current with the condenser method, there are oscillations set up due to corona disturbances, which, of course, take place at the peak of the wave, which may not be taken into account in the average value of the charging current of the condenser, so that it is possible that the effect of the corona in the wires, etc., vitiated our tests slightly. But I do not think that this can account entirely for the large discrepancy between the theoretical figures and the figures obtained by test. It seems to me that the lower breakdown spark-over voltage of large spheres, as compared with small spheres, must be due to some external effect. Perhaps it is a question of free ionization in the air; it seems probable that the largest sphere collects

its electrons and positively charged molecules from a very much larger volume of space than the smaller spheres. The positive charges will be drawn toward the electrode that happens to be negative at a certain instant, and the negative will be drawn toward the positive. While these charges do not cause immediate breakdown, their presence will increase the intensity at the surface, they will tend to accumulate at the point of highest potential gradient and finally, on the largest spheres, increase the intensity sufficiently to cause spontaneous ionization.

Referring to the paper by Messrs. Whitehead and Gorton, their modification of the method first used by Mr. Chubb and myself, to meet the exigencies of the high-frequency test, is very interesting, but there is a question in my mind whether the rectifier does not produce superimposed oscillations of its own. In other words, as I see it, in their circuit they introduce what amounts to a square-topped alternating wave which has an infinite number of frequencies. It is possible for conditions to arise such that any one of this infinite number of harmonics may resonate, causing a high peak in the voltage, which may be of such frequency and characteristics that its true value is not properly recorded.

Another possibility of error suggests itself to me in Dr. Whitehead's tests. I do not think it safe to assume that the rotating field of the generator has sufficient inertia to prevent it from causing troubles due to surges in the supply circuit. Our experience in the first calibration of the sphere spark gap showed that even with an armature running at very high speed, supplying alternating current to the testing transformer, the effect of surges in neighboring circuits was noticeable—we had a neighboring three-phase grounded crane circuit, in which heavy loads were suddenly applied, and we found this had a great effect on our testing voltages. Every time the crane hoist started, we would have a breakdown and oscillation, in spite of the fact that the two systems were connected only through mechanical parts having considerable inertia. The reason, as I understand it, is that any slight oscillation in the mechanical part will set up an oscillating voltage, which may in itself be small, but under certain circumstances the oscillation may have the same period as the test circuit, and cause quite high oscillating voltages.

Probably either of these two possibilities may explain the results that Dr. Whitehead found—namely, that at certain definite points there was an apparent discontinuity in the corona point.

In connection with the question of resonance in transformers, we had some experience which led us to try to find some way of getting an absolute method of measuring maximum voltage without having recourse to ratio. Our shop testing force had an experience several years ago with a high-voltage transformer

which was to be tested for certain overload capacities. They could not get the transformer past the testing floor. Every time they tested it by the ratio method, they failed. For some reason or other it never occurred to them to use the sphere gap to find out what was the trouble. I was asked to go down and investigate the matter. I suggested that we try to see what the sphere gap showed. We found in the case of one generator a test value above that shown by ratio all the way from zero to 60 per cent on the high-tension side, purely due to wave distortion and resonance of the distorting harmonic. It is never safe to trust to ratio on tests with very high-voltage transformers, on account of the fact that the capacity of the transformer is necessarily quite large.

Referring to the paper by Messrs. Clark and Ryan, I wish to ask the authors if they assume that the wave form of an oscillating circuit is so close to a sine wave that it cannot affect the maximum value of the voltage. We have had waves of applied voltage that looked like almost perfect sine waves, which gave waves of charging current with condensers which showed distinct harmonics. The multiplying factor of the higher harmonics is very large, so that even a very small fraction of a normal frequency would be magnified and multiplied, through resonance, enough to have a large effect on measurements, resulting in large discrepancies from the values indicated by ratio.

I note another thing in the paper by Messrs. Clark and Ryan, and that is that their spheres are isolated, and they have no distinct zero potential point in their system. In such a case we have no idea what the relative potentials of the spheres are. The whole system may oscillate at a high frequency above zero, so that the maximum intensity at the spheres of such a system is quite indefinite. For that reason, I am inclined to think that these tests cannot be considered as final.

A point Messrs. Clark and Ryan bring out in their paper, which I think is very important, is the question of the weight to be given in test measurements in connection with such a piece of apparatus as the spark gap; the sphere gap particularly. In studying the sphere gap, it has a maximum breakdown, which is the voltage we wish to arrive at. Our tests are possibly subject to extraneous conditions, such as surges in neighboring circuits, etc., and also to fluctuations, breakdowns due to the oscillation and consequent fluctuation, but if measurements are carefully carried out, it is not possible to obtain values higher than the actual breakdown voltage. So that in using the results of such tests the average of a large number of tests is not necessarily the correct value, but rather greater weight should be given to the maximum values, in other words, any discrepancy will be of lower value than the actual true strength, and is probably due to the oscillation or some trouble in the circuit itself.

Referring to the maximum voltage meter, as I have called it—the method that Dr. Whitehead has used and which Mr. Chubb

and I used in the original paper on the calibration of the sphere gap—I may state that it gives what may be called the average maximum value. In other words, it cannot show the maximum value that may occur at any one cycle, due to some external effect; if there is a difference in the positive and negative wave form, or change, during a very short length of time, this cannot be shown. It simply indicates the average of a consecutive series of waves of charging current, and gives the average maximum value of applied voltage for the consecutive series. In order that this shall be the true maximum value, it is necessary to presuppose a steady and constant applied voltage and a constant secondary voltage.

The vibration of the suspended wires, mentioned in the paper by Messrs. Whitehead and Gorton, I have also observed at corona points on wires with neighboring large bodies.

D. D. Ewing: I believe we all realize that one of the greatest difficulties we have to encounter in the study of high-tension phenomena is the difficulty of making the measurements with any degree of scientific accuracy. The points I have in mind were brought up by Dr. Whitehead's paper. I believe Mr. Fortescue, if I understood him correctly, touched on one of them, namely, the deformation of wave form when the mercury arc is used as a rectifier. I notice that Dr. Whitehead in his experimental work made use of a direct-current measuring instrument, presumably of the permanent magnet moving coil type. He states in his paper that the permanent magnet type instrument is suitable for the purpose although he does not specifically state that he made use of this particular type of instrument. I would like to call attention to the fact that some of the common commercial forms of this type of instrument can not be relied on to give a very high degree of accuracy, when used to indicate the average value of a fluctuating quantity. In some tests made several years ago, on some meters used in railway service, I found that the average value was about 15 per cent off. In the measurements made by Dr. Whitehead, the errors introduced by the use of the mercury arc and this type of instrument would be differential rather than cumulative, thus giving a low resultant error. I wish, however, to call attention to this fact about the direct-current permanent magnet instrument: it must be used with caution if the quantities are fluctuating rapidly.

E. E. F. Creighton: I think the most evident thing in all these papers and in all the discussions which have taken place in the past few years has been the lack of some instrument or some device that will accurately measure the voltage. If such an instrument were available at the present time, the whole subject could be cleared up.

Every one of these papers adds a little more, makes one step nearer the final solution, by giving the results of some method which has been tried out for the measurement of voltage at high

frequency. We have endeavored in the study of lightning arresters for many years to get something we could rely on. Our endeavor has been, not so much to locate a condition and measure the voltage, but to vary all the conditions and get the minimum gap length as near as we could for the same voltage impulse applied.

In working with Alexanderson's alternator, running up to 200,000 cycles per second, one of the first difficulties encountered was the impossibility of getting any definite voltage ratio in the transformer. We had a transformer made up of eleven layers, and used one layer as a primary and the other ten layers as a secondary, stepping up 1 to 10. We found at a certain frequency when 100 volts was applied to the primary we got 100 volts across the secondary. Instead of getting 1 to 10, according to the ratio of turns, we had a ratio of 1 to 1. Then we took our voltmeter and applied it to the different layers, and found one layer that was given a ratio of ten times the impressed voltage, in other words, 1000 volts, where the ratio of the number of turns was only 1 to 1. This simple illustration shows the effect of internal capacity in entirely changing the voltages that should be given by the ratio of the number of turns.

In regard to the free ionization in the air, we have had by tests in the laboratory a number of illustrations of this ionization effect. The vacuum arrester consists of a copper tube with an insulated electrode on the inside and more or less vacuum produced around these electrodes, depending on the spark voltage desired. The gap length is of the order of 1 mm. and the diameter of the tube only about $\frac{3}{4}$ in. (about 19 mm.). When potential is first applied the sparking voltage may be 500 volts. If potential is applied immediately afterwards a lower value is needed to cause a spark—even as low as 350 volts. It requires considerable time, a number of minutes, in some cases a number of hours, for this internal ionization to disappear.

Another case of ionization was illustrated in the test we showed before the Institute something over a year ago, in which we recommended the use of high frequency for the testing of insulators. It is shown in all of these tests that when high frequency is applied to an insulator there are obtained many sparks that are fairly evenly distributed around the surface of the insulator. These sparks are not simultaneous, but successive. The explanation of the distribution may be that when the potential is applied to the cap of the insulator it ionizes more or less evenly the atmosphere all over the surface of the porcelain. Due to accidental conditions, the first spark will break over at some one point. In so doing, it will relieve the stress in the atmosphere at that point. The subsequent sparks will find points in the atmosphere elsewhere that are highly ionized and the subsequent sparks will consequently take other paths. I think this is another illustration of the fact that ionization may reside for a considerable time in the atmosphere.

Professor Caldwell brings up a very pertinent question, that is, in using resistance in series with spark gaps, is the testing outfit still applicable for the testing of apparatus? While series resistance is desirable as recommended, there is a special condition where it is not applicable. It is not applicable to the testing of lightning arresters. A series resistance of one ohm per volt will give erroneous results in the testing of arresters. We have used for many years without series resistance a transformer at 100,000 volts for testing work, and in only two cases during all that time have oscillations been produced which damaged the end turns.

Mr. Peek has brought out definitely that moisture in the atmosphere causes an increase in the spark potential of a needle gap (but not of a sphere gap).

It may be of some interest to note that in the testing of multi-gap lightning arresters the opposite effect is sometimes found. For example, a compression chamber lightning arrester tested on a perfectly dry day had a certain sparking potential. Three days later on a humid day and without any changes in the circuit the spark potential was considerably lower. From a certain point of view, that is a valuable thing to know. When lightning is about to take place, the arrester will be a little more sensitive.

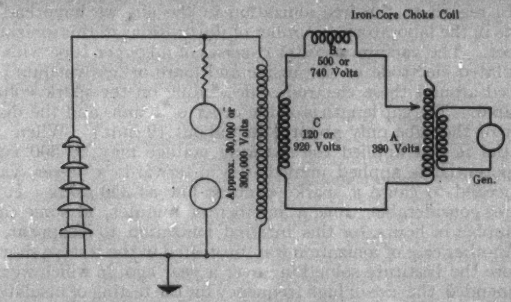

FIG. 1

H. B. Dwight: In Mr. Peek's paper are given various precautions to be observed in making high-voltage tests. Although the list was not meant to be complete, I would suggest adding to these the avoidance of the use of choke coils with iron cores, even in the low-tension circuit. There is a tendency to use such coils in practical testing because small transformers or auto-transformers are generally available in many sizes, while air coils are not. The iron-cored coils may not always produce trouble, but there is distinct danger of it, as is shown by the following experience encountered in routine commercial testing.

In testing some insulators at 300,000 volts, an iron-cored choke coil was used as at *B*, Fig. 1. On applying a low-tension voltage

which normally gave about 130,000 volts, an entire absence of corona was noted. On again closing the switch with exactly the same connections there was a heavy continuous discharge over the insulator, indicating much more than 130,000 volts. Repeated closing of the low-tension circuit gave sometimes one and sometimes the other of these two steady conditions.

In locating the cause of this trouble, it was found by measurements of the voltages on A, B and C that the voltages on the insulator in the two steady states were about 30,000 and 300,000 and that the choke coil was in the one case unsaturated and in the other case, saturated. Which state was produced depended apparently on the part of the voltage wave at which the circuit was closed. Both states were steady except that sometimes the first would suddenly change into the second, with corresponding increase in voltage.

The vector diagrams for the two different steady states with the same applied voltage of 380 volts, are shown in Fig. 2.

An indication of how the saturation of the iron core produces

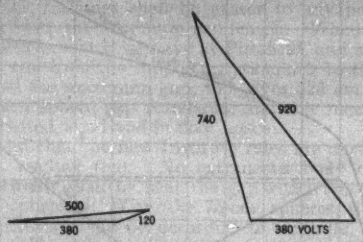

FIG. 2

the erratic results is shown in Fig. 3. The curve of applied voltage is to be calculated from the capacity of the insulator and the magnetizing current and iron loss current of the choke coil. For details of this calculation see the *Electric Journal*, p.1102, December, 1911. The current and voltages have been observed with an oscillograph and have been found to have the same frequency as the generator, and to have phase relations in agreement with the vector diagrams.

The phenomenon is essentially a low-voltage, standard frequency phenomenon of continuous duration. It has no connection with the high-frequency oscillations which occur around a spark gap and it is quite distinct from the phenomenon of simple resonance. The two different voltages obtained from one connection of apparatus depend on the combination of leading current and an iron magnetic circuit which becomes saturated. It is seen, from Fig. 3, that a certain value of applied voltage may correspond to two different values of amperes, according to a point in the part $U\ R$, or the part $T\ S$, of the curve for applied

voltage. These two values produce two different values of voltage on the testing transformer, the curve for which is seen to be in two parts, separated by an unstable region.

In investigating this phenomenon, the applied voltage may be slowly increased from U to R, and then the current will suddenly change from R to S. Thus, about ten times as much current will flow through the choke coil, and a high voltage will be produced. Then, on lowering the voltage gradually from S to T, the current drops suddenly from T to U, and the original condition is obtained.

Since a choke coil with an iron core may render indeterminate the voltage to be obtained from a given arrangement of appara-

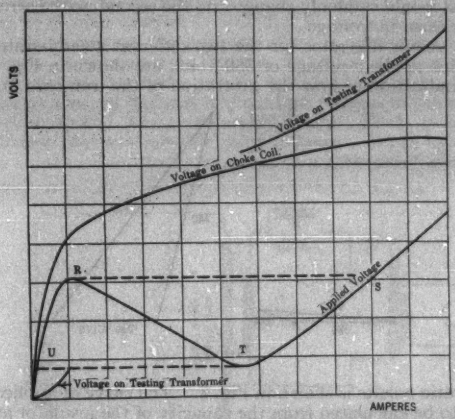

FIG. 3

tus, and may give suddenly a far greater voltage than would be expected, its use would appear to be inadvisable.

W. W. Lewis: Mr. Peek says that carbon or graphite rods should be avoided as resistance in series with the sphere gap, because they are unreliable. We have found in Pittsfield that this is usually true with the so-called "high-rated" carbon rods, that is, rods that are rated in the neighborhood of 60,000 ohms each, because these rods contain very little carbon; they are composed of some kind of clay mixed with graphite, and their resistance changes when current is passed through them. The "low-rated" rods, *i.e.*, rods rated in the neighborhood of 4000 ohms each, we have found to be very constant and reliable. We have checked these by measuring the voltages set up in the high tension of the transformer under test, when the spark gap

is arced over as shown in Mr. Peek's Fig. 13, and we find that we get no appreciable voltage set up in the high tension of the transformer when resistance is used to the value of one ohm per volt or over. We have also run heat tests on these rods and find their resistance to remain constant, whereas that of the high-rated rods increases appreciably.

We have tried metallic resistance and find that in order to get high resistance, very small wire must be used, and to prevent this burning out, it must be immersed in oil. It is very difficult to prevent the oil from leaking and to insulate the resistance properly. Water resistances are subject to the trouble that steam forms at the terminals and the water explodes violently from the tubes. We have decided that, altogether, the low-rated carbon rods are nearest to the ideal.

Mr. Peek in his precautions says: "The spheres should be twice the gap setting from surroundings." It is rather indefinite as to just what this means. We have interpreted it at Pittsfield to mean that no part of the wooden supporting standard or metal shank bushings shall be nearer to any point of the spheres than twice the maximum gap length. When you figure on 75-cm. spheres, which we have at Pittsfield, and allow a distance of 150 cm. from the supporting standards to the spheres, and 75 cm. as the maximum gap, this gives 525 cm., or about 17 ft., between sphere gap standards, and this means a great expense in treated wood and in floor space.

I understand that the new Institute rules are more lenient in this respect, reading that "No extraneous body or external part of the circuit shall be near the gap within twice the diameter of the spheres." With the 75-cm. spheres, the distance between standards would be, according to this rule, 375 cm. or about 12 ft. The rule might well be further modified, a distinction being made between bodies that are insulating, and metallic bodies.

We have made a few tests recently to check the effect of wood, metal and porcelain on the sphere gap arc-over, when these objects are placed at different distances from the spheres, and we find that wood and porcelain have practically no effect when placed as close as one-half the gap distance away from the spheres. Metal, however, appreciably reduces the spark-over, that is, when a sheet of metal was placed one and one-half times the gap distance away from the spheres, the spark-over voltage was reduced four per cent.

Mr. Fortescue questioned the statement in regard to the effect of metal on the shanks. To check this we made some tests, placing a disk of a diameter equal to the diameter of the sphere (12.5 cm.) on the shanks at different distances from the sphere, and we found that when this disk was placed on the shank of the non-grounded sphere (these tests were all made with one sphere grounded) it made as high as 3 per cent difference in the spark-over. These values were checked several times,

the voltages being determined by a voltmeter coil placed in the center of the high-tension winding of the testing transformer. We have found the voltmeter coil to be very accurate and valuable for this kind of work.

E. P. Peck: I want to ask Mr. Peek what he meant by saying, on page 945, "For steep wave fronts a higher voltage is required to spark over a given gap than for low frequency." The rest of the paper indicates that the higher the frequency the lower the spark-over. This one remark indicates the other direction.

J. R. Craighead: A previous speaker mentioned the practise of using the voltmeter coil in the middle of the transformer as a means of reading the voltage, and at the same time spoke of using one of the spheres as grounded. Now, it sometimes becomes convenient to ground the transformer in the middle when the voltmeter coil is there, to protect the voltmeter coil. I would ask Mr. Peek if he can tell us anything about the relation of this to the grounded curve and the ungrounded curve. Also, what is the effect of the ground placed at some other point in the circuit?

F. W. Peek, Jr.: Mr. Chubb states that after a given high voltage is reached, spark-over will result between spheres, no matter how far the gap length is increased. In other words, the law which I have given suddenly ceases to hold. The curve becomes discontinuous.

Theory at once explains this discrepancy, when the cause may be readily corrected or removed in *practise*. The curve is really continuous. The reason for the discrepancy is as follows:

The spheres with their connecting leads make up a circuit of capacity and inductance. A local spark-over or static spark on a section of a supporting bushing, from the end of a connecting wire, etc., will cause a readjustment of energy distribution in the circuit. An oscillation or high transient voltage results, which is superposed upon the applied voltage and causes the sphere gap to spark over. The actual voltage at the sphere gap may thus easily be double the applied voltage, or the voltage read at the meter. The sphere gap may thus, under this condition, be lengthened out to a considerable extent, or to the limit of the transient voltage, and spark-over will result. The sphere measures the transient voltage and not the applied voltage. The applied voltage at which the curve appears to become discontinuous, is the critical voltage for local breakdown somewhere, as on leads, etc. The transient follows. The effect may be easily reproduced in the laboratory at fairly low voltages. It is more likely to occur in practise at high voltages because static sparks are most likely to occur at high voltages. The remedy is to arrange leads and conductors so that local static sparking does not occur and so that the gap supports are insulated to withstand the voltage to be measured. The resistances should be placed directly in series with the gap and as near the

spheres as possible. The sphere gap is much more sensitive to transient voltages than the needle gap. Care must always be taken to prevent these voltages reaching the gap, unless it is desired to measure them.

As an example: A sphere gap without series resistance was placed in parallel with a string of insulators, and voltage applied. The known arc-over of the insulators was 300 kv. The sphere gap was set for that voltage. At 295 kv. static sparks occurred on the insulator unit near the line end. The sphere gap sparked over, due to the resulting high transient voltage, and relieved the pressure. The gap was lengthened. At 295 kv. the transient again occurred and caused the sphere to spark over. It was in this way necessary to increase the sphere gap to a spacing equivalent to 400 kv. before the insulators sparked over. The spheres in this case measured the transient voltage. In such tests it is preferable to use the spheres only to calibrate the wave shape and transformer ratio. This should be done at a voltage below that at which static sparks appear on the insulator.

We have, since the paper was written, actually checked a calculated curve for 75-cm. spheres up to 700 kv. with good agreement. It was, of course, necessary to use a very well insulated stand and leads, etc., at this voltage.

The effect of altitudes must be the same at high voltages as at low voltages. At high voltages the spacings are greater than at low voltages; the resulting gradients upon which the breakdown depends are the same. In my former papers I have shown that the decreased strength of air at high altitudes is the result of decreased air density, and that the effect is the same whether the change in density is due to temperature or to pressure.

Mr. Dwight's discussion is interesting. I should like to see the data.

The term "high frequency" is at present very loosely used and under it are included continuous high frequency, and transient voltages, as oscillations, steep wave front impulses, etc. The effects of these are naturally quite different. There are, in this way, many apparent discrepancies in the effects resulting from the "same" cause—"high frequency." The term is thus used to explain many "mysterious" failures. The sphere gap, when the maximum spacing is limited to the diameter of the spheres, measures with fair approximation high frequency, and transient voltages. In case of high frequency care must be taken to polish carefully the surface of the sphere. The needle gap does not even approximate such voltages. At continuous high frequency the needle gap curve is changed by the intense local heating; at steep wave front by the limited time. This is discussed in my paper. I have given a theoretical explanation in former discussions.* It may be of interest to give an example of impulse voltage here:

*Page 138, this volume.
"High Voltage Engineering", *Journal* of Franklin Institute, Dec. 1913. Page 612, this volume.

Spacing of Needle cm.	Voltages Required to Cause Needles to Spark Over			Ratio	
	60 cycles max.	Impulse voltage (measured by 25-cm. spheres, using 60-cycle curve)	Impulse voltage calculated from circuit constants	Calculated impulse voltage / 60 cycles	
				Needles	Spheres
2.3	26.0	36.6	39.5	1.41	1.08
3.95	39.5	59.5	60.5	1.45	1.02
5.34	51.5	73.5	74.5	1.45	1.01

A higher impulse voltage is required to cause the needles to arc over than at 60 cycles. The spheres arc over at approximately the same voltage at 60 cycles and impulse. This particular impulse reached its maximum in 0.00045 milliseconds. A steeper impulse would require a still higher voltage on the needle gap to cause arc-over; with continuous high frequency the needle sparks over at lower voltages than at 60~. Great caution is thus necessary in making "high frequency" tests. Much damage may also be done to apparatus, etc., as I have pointed out, unless tests are made with caution. Care should be taken to place the spheres at a considerable distance from ground and from large metal or other conducting masses. In no case should this distance be less than twice the sphere diameter. This is so whether both spheres are insulated or one sphere is grounded. The curves for both spheres insulated were made with the neutral at midpoint. To be sure of this, it is desirable that the transformer neutral be grounded. Carbon rods may be made in which the resistance is not greatly affected at high voltages, but rods as generally made are affected.

Dr. Whitehead has developed an extremely interesting method of measuring high-frequency voltages. I have also noticed the phenomenon of vibrating wires which Dr. Whitehead mentions. Photographs showing this are given in my 1912 paper.

Referring to Fig. 5, in the paper of Messrs. Clark and Ryan, I would like to call attention to the fact that at small spacings the 60-cycle curve is also approximately a straight line. At higher voltages the high-frequency curve will bend as the 60-cycle curve does. For 7-in. (17.8-cm.) spheres, curve III will fall closer to I and II.

John B. Whitehead: It is interesting to ask, in connection with this question of frequency, to what conclusion these papers lead us. Considering the ascending range, there is evidence from our experiments that with increasing frequency there is a

slight, but certainly evident, lowering of corona-forming voltage. There have been one or two suggestions, by Mr. Fortescue and others, of possible sources of error, and at first glimpse it appears that these errors, if they exist, would be in the direction of lowering the apparent corona voltage. In my opinion, however, these errors are not present.

In Mr. Peek's range of frequency, up to 40,000 cycles, a further lowering is indicated; and then going up to the maximum range, Professor Ryan has a still further lowering. In the case of oscillating circuits, long associated in our minds with brush discharges, it would not be an astonishing thing to find that at higher frequencies we would have lower corona-forming voltages. At the same time, high values of peak voltage which cannot be detected often occur in oscillating circuits, so it is not necessarily the case that we must have a lower corona voltage in a high-frequency circuit, simply due to the higher frequency.

In Mr. Peek's description of the experiments at 40,000 cycles, he suggests that if his spheres had been more carefully cleaned he might have gotten a discharge voltage which would be more nearly that observed at commercial frequencies. He also measured his voltages, as I understand it, with an electrostatic voltmeter. Although he states that correction has been made for wave form, the static voltmeter measures effective values, and it would be interesting to know how he has applied correction at these frequenceis.

The observations reported in the paper by Messrs. Clark and Ryan, as to the ratio of lowering at still higher frequencies, show a remarkable lowering of corona voltage. It is to be hoped that Professor Ryan will repeat some of his interesting experiments and corroborate the present results beyond question.

Summing up the three papers, there is a distinct evidence of lowering of the corona voltage with increasing values of the frequency. The amount of that lowering is apparently small, except possibly at very high frequencies. For these high frequencies more observations are desirable.

With reference to Mr. Fortescue's suggestions as to possible errors in our observations due to the presence of the mercury gap and the inertia of the generator, we did not use the mercury arc itself as a rectifier. Our two mercury arcs were excited by independent continuous-current circuits, and we had the auxiliary electrodes in the mercury tube, simply using the very copious ionization which is always present in a mercury arc as a conducting path which had, of course, only unipolar conductivity. The very small current carried, and the fact that the tube was in series connection, indicate oscillation as a very remote possibility. At the same time, the suggestion is possibly an explanation of the unstable conditions in the region near 400 cycles where we found evidence of resonance.

The inertia of the generator was simply mentioned as one of the factors which led us to believe that we had stable conditions,

conditions which were uniform at all times, and our observations were repeated so definitely throughout that there is hardly a chance for error on account of the possible fluctuation of the mass of the armature.

In reference to Mr. Ewing's comment on the possible error in using a permanent magnet type of instrument for recording average values, this type of instrument has been used for taking average values ever since the days of the first contact makers for measuring wave forms. It would be interesting to know for what range of pulsations Mr. Ewing made his observations. We are, of course, working here up between one thousand and three thousand cycles, far above the highest commercial frequencies.

Before closing the meeting, I would like to report an experiment which has recently been made abroad, the news of which has come to me in a letter. It is a matter of very great interest and with your permission I will take about five minutes to tell you about it. There has been no official publication of it as yet, but the publication will follow, and the word that comes to me from one of my colleagues who was present, and saw the experiment, is what I wish to report to you.

We are all familiar, of course, with the mechanical analogies that are drawn between electric circuits and the motion of masses, in which we consider inductance as mass, capacity as elasticity and resistance as the friction in a mechanical system. If we follow this analogy, and hark back to one of Newton's laws, that a body will persist in its state of motion unless acted on by some external force, it will explain the experiment in question. If we could realize mechanically the motion of a body absolutely free from all friction, the body would go on moving indefinitely.

Professor Kamerlingh-Onnes of Leyden has produced the current which does not die out, and which is not excited by any electromotive force, thus realizing the analogue of the moving mass free of all friction. The experiment is briefly this: He takes a coil of fine lead wire of about 1000 turns, and about 2 cm. in diameter, and short-circuits it on itself. This coil is placed in a strong magnetic field, the lines of force threading this round coil. A vessel of liquid helium is brought up so that the wire may be immersed in it, while still remaining in the magnetic field. The liquid helium sets up temperatures which are far lower than any temperatures we have known, even lower than the temperatures that may be got from liquid air and liquid hydrogen, temperatures which are at least in the neighborhood of the absolute zero. If you take curves showing the relation between the specific resistances of materials and temperature, these curves for all substances are all straight lines and all tend down to the absolute zero, indicating that the resistance would become zero if the temperature were extended to the absolute zero. The liquid helium brings us nearer to it than

we have ever been before. Now, with the helium, we have a coil of lead wire in a strong magnetic field, and at a temperature, we will say, in the neighborhood of absolute zero, minus 273 deg.

Under these circumstances the circuit of the exciting magnet is broken, inducing an electromotive force and consequent current in the short-circuited coil, which is near absolute zero, and therefore near zero resistance. Consequently, there is no frictional element, no damping factor, if you please, and the current should go on indefinitely since the coil has no resistance. It went on during a period of four to five hours, which was stated as the time of observation of my friend. There was no indication of a diminution of the current in that coil at the end of from four to five hours.

M. G. Lloyd: What was the evidence that the current was continuing?

J. B. Whitehead: It was not stated. The exciting circuit was broken, and the exciting magnet removed. I should imagine the evidence would be the influence of the coil on a magnetometer needle. It seems the most obvious way.

W. B. Kouwenhoven (communicated after adjournment): The three excellent papers presented under the auspices of the Electrophysics Committee all had to do with high voltages, and in all of them the accurate determination of the voltage plays a very important part. I wish to bring to the attention of the members a method for measuring the effective value of alternating-current voltages, which has a very high degree of accuracy. This method consists, briefly, in using a high resistance connected in series with a small resistance across the high-voltage terminals, and measuring the drop of potential across the small resistance with a quadrant electrometer.

Suppose that a high resistance R and a small resistance r be connected in series across a potential difference of V volts, and that the drop of potential across the small resistance is v. Then $V = \frac{R + r}{r} v$. This method, when used for direct current and low voltages, is simple and accurate. When applied directly to alternating currents and high voltages, however, it is no longer accurate, because of the capacity currents which flow not only from the resistances to earth but also between the different parts of the resistances. On account of this the current passing through the resistances can no longer be considered as quasi-stationary; the ratio

$$\frac{V}{v} = \frac{R + r}{r}$$

holds no longer, and the voltages in different parts of the resistances are in phase neither with each other nor with the total voltage. It is possible, however, so to construct the resistances that the inaccuracies are eliminated.

Let us consider such an arrangement of resistances theoretically. Suppose that the large resistance be divided up into n units or divisions R_1, R_2, R_3, ... R_n, and that these are so small that we may consider the current in each to be quasi-stationary, and that the current in going from division to division changes slightly in value and in phase. This arrangement is illustrated in Fig. 4. One terminal of the high voltage is connected to the resistance division R_n and the other to R_1 and at the same time to earth. Now in R_n the capacity currents to earth are the largest and these currents are ahead of the total voltage in phase. Therefore the voltage drop v_n in this resistance unit leads the total voltage V. The voltage drops in the various resistance divisions and the total voltage form a polygon as shown, and it follows that the voltage drop in R_1 lags behind the total voltage. Voltage measurements are

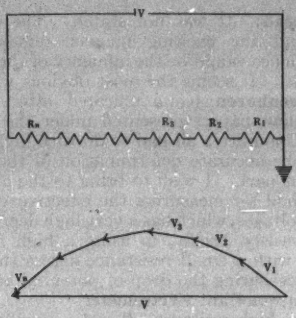

FIG. 4

usually carried out at the earthed pole and the problem resolves itself into bringing the current and voltage in R_1 into phase with the total voltage, and in determining the value of the ratio between V and v.

A set of eight resistance units based on this principle was built in the laboratories of the Reichsanstalt, Germany. The German resistance units were wound with manganin wire; the maximum voltage drop per unit, without over-heating, was 3000 volts. I built a set of resistance units using a liquid resistance as a substitute for the wire resistances in order to determine if, by so doing, it was possible to increase the voltage range of the apparatus and to use an electrolytic resistance for this purpose. The electrolyte was the so-called Manganini solution, and proved very successful.

Each resistance unit consists of a Jena glass tube which contains the solution. These tubes are about a meter in length,

have a diameter of approximately 1 mm. and are fitted with expanded ends to allow room for the electrodes. With tubes of these dimensions it is possible to construct a resistance unit of 24 million ohms per meter length. In order to define the capacity to earth, each tube is fitted with a metal cylinder slightly longer than the tube and of 10 cm. inner diameter. These cylinders are well insulated from the Jena glass tubes and the entire arrangement may be regarded as a cable whose central conductor has a high resistance per unit length. In order to bring the current at the earthed pole into phase with the total voltage V, it is necessary to apply a voltage to the metal cylinders such that there will exist a certain definite difference of

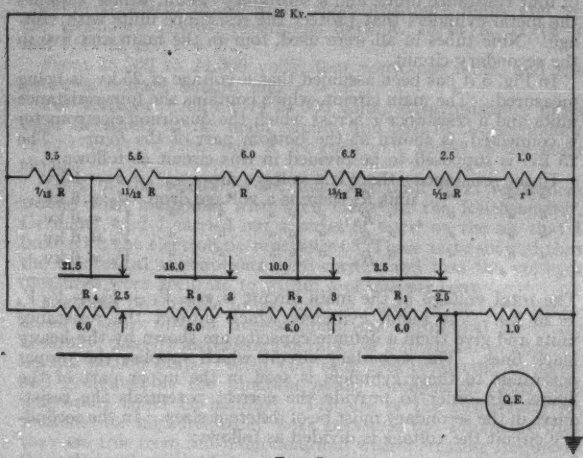

FIG. 5

potential between the earthed end (end of tube nearest earthed connection) of the tube and its protecting cylinder. The so-called telegraph formulas of Maxwell apply to a cable of this construction, and, by solving them, it is possible to ascertain what this potential difference should be.

The Manganini solution or the $\frac{2}{3}$ normal manitol, boric acid, calcium chlorid solution was used as the electrolyte. According to Maltby[1] this solution contains:

manitol	121.1 grams per liter
boric acid	41.2 grams per liter
calcium chlorid	0.06 grams per liter.

1. Maltby, *Zeitschrift. f. Ph. Ch.*, 18, S. 133, 1895.

To this solution I added one part of distilled water. Under these conditions the solution has a conductivity of about 0.00044 and between the limits 17 deg. and 24 deg. cent. the change in the resistance is less than 1/10 of one per cent.

The electrodes were of platinum and were plated with spongy (black) platinum in order to reduce the polarization to a minimum. The phase displacement due to the polarization was measured and found to be about two seconds of arc at a frequency of 50 cycles and with a current density of from 0.3 to 2.0 milliamperes per sq. cm. of electrode surface.

The resistance set which I built consisted of four resistance units. The set has two circuits, a main circuit, which consists of four resistance units, and a secondary circuit, which supplies the metal cylinders that protect the resistance units with voltage. Nine tubes in all were used, four in the main and five in the secondary circuit.

In Fig. 5 it has been assumed that a voltage of 25 kv. is being measured. The main circuit, which contains the four resistance units and a resistance r across which the quadrant electrometer is connected, is shown at the bottom part of the figure. The 25 kv. is supposed to be divided in this circuit as follows:

In the resistance r there is a voltage drop	$v = 1$ kv.
" " " unit R_1 there is a voltage drop	$V_1 = 6$ kv.
" " " " R_2 " " " " "	$V_2 = 6$ kv.
" " " " R_3 " " " " "	$V_3 = 6$ kv.
" " " " R_4 " " " " "	$V_4 = 6$ kv.

The total voltage in the main circuit is $v + V_1 + V_2 + V_3 V_4 = 25$ kv. The metal cylinders which protect the resistance units and give them a definite capacity are shown by the heavy black lines. The secondary circuit which supplies the proper potentials to these cylinders is seen in the upper part of the figure. In order to provide the correct potentials the resistances in the secondary must be of different sizes. In the secondary circuit the voltage is divided as follows:

In the resistance r' there is a voltage drop of	1.0 kv.
" " " 5/12 R there is a voltage drop of	2.5 kv.
" " " 13/12 R " " " " " "	6.5 kv.
" " " R " " " " " "	6.0 kv.
" " " 11/12 R " " " " " "	5.5 kv.
" " " 7/12 R " " " " " "	3.5 kv.
The total voltage in the secondary circuit is	25.0 kv.

The potential differences between the tubes in the main circuit and their protecting cylinders are also shown in the figure. There are, for the end resistance units R_1 and R_n (in this case R_4), 5/12 of the voltage drop per resistance unit or 2.5 kv.; for all other resistances $R_2, R_3, \ldots$, ½ of the voltage drop per unit or 3.0 kv. The tubes or resistance units in the main circuit are

all of the same size and have been designated by the letter R. The tubes in the secondary circuit are of various sizes, which have been given in terms of R, thus: $5/12\ R$, $7/12\ R$, etc.

With this set it is possible to measure voltages as high as 27,000 volts with all four resistance units in the main circuit, but for lower voltages it is advantageous to use fewer tubes. I should recommend the following combinations of the resistance units:

Up to 6000 volts, one resistance unit, and, in the secondary circuit, resistances $5/12\ R$ and $7/12\ R$, and $r = r'$.

From 6000 to 12,000 volts, two resistance units, and, in the secondary circuit, resistances $5/12\ R$, R and $7/12\ R$, and $r = r'$.

From 12,000 to 18,000 volts, three resistance units, and, in the secondary circuit, resistances $5/12\ R$, $13/12\ R$, $11/12\ R$ and $7/12\ R$, and $r = r'$.

From 18,000 to 24,000 volts, four resistance units, and the entire secondary circuit, and $r = r'$.

For voltages much above 24,000 volts, extra resistance units must be added to the main circuit, and also in the secondary circuit an extra resistance R for each unit added to the main circuit.

Tests of the resistance set that was built from resistances wound with manganin wire were made[2] at the Reichsanstalt, Germany, and I carried out a series of tests[3] on the set that I built with the electrolytic resistances. These tests showed that the theoretical assumptions were correct and that the voltages measured were accurate to within $\frac{1}{2}$ of one per cent.

It should be possible to use eight of these electrolytic resistances in series without over-stepping the theoretical limits for accuracy, thereby increasing the range of a single set to approximately 50,000 volts. With two such sets connected in series and grounded at the junction point, voltages of twice that magnitude could be handled. The use of the electrolytic resistances for high-frequency work possesses the advantage that they are free from self-induction, and with increasing frequency the polarization would disappear entirely.

Three voltage transformers were tested for the constancy of the ratio of transformation. The primary voltage was measured in each case by a Weston a-c., d-c. voltmeter. The ratio of transformation was found in every case to be constant to within one per cent from about half voltage to full rated voltage of the transformer. For low voltages, however, the ratio of transformation gave results that were in some cases as much as four per cent too high, the error decreasing more or less gradually as half rated voltage was approached. Therefore investigators should be very careful when making high-voltage tests not to rely too much upon the ratio of transformation.

2. Orlich and Schultze, *Archiv. f. Elek.*, 1, S. 1 and 88, 1912.

3. Kouwenhoven, *Washington Univ. Studies*, Vol. 1, p. 143, 1914.

Harris J. Ryan (by letter): Replying to Mr. Fortescue's questions: The high-frequency driving voltage of the arc was multiplied about one hundred times by resonance. The impressed voltage of the arc having an irregular wave form was consumed in the first few turns of the outer helices. Thus in a given case the potential to neutral of the sixth turn from either arc terminal would, on test, be found at low (almost zero) alternating potential. On either side of this turn the potential would be found to rise regularly. By theory, under these circumstances, it is difficult to understand how the high-potential wave form can have departed appreciably from that of the true sine wave. The cyclograph traced a quadrature combination of current and potential waves. The result was a true ellipse with no evidence of the presence of harmonics. In regard to the use of isolated spheres made necessary in the method devised to eliminate harmonics in the high-frequency high voltage: The case is not one of actual isolation, as assumed by Mr. Fortescue. The arc was supplied with current from two 600-volt direct-current generators connected in series with their neutral grounded. Furthermore, the oscillating circuit would fail utterly to operate unless both sides of the circuit were nicely balanced, developing substantially equal voltages.

We are not asking that our results be accepted as final. The art of generating and handling high-frequency high voltages is undeveloped as yet. It would not be reasonable to expect final results at this time even with the high-frequency alternator driven at *constant speed* as suggested by one speaker.

In his closing remarks Mr. Peek has accounted for the erratic behavior of the sphere gap voltmeter, cited by Mr. Chubb, when in action above 320,000 volts. He presents his method for eliminating such behavior. Closely related hereto are two experiences encountered in our work.

Regarding the first experience—we have mentioned in our paper that we could not use the condenser voltmeter to measure voltages beyond 50,000. Discharges through the four-inch (aggregate) gap in the two pairs of 7- and 11-inch concentric cylinders, six feet in length, would occur in an erratic fashion at voltages above 53,000. In planning this apparatus we had concluded from the results of Fortescue and others that such discharges should not take place at voltages below 165,000. We expected, therefore, to use the cylinders and instruments with safety for authenticating voltages as high as 125,000, *i.e.*, to the limit of the high-frequency voltage capacity of our equipment. Since the completion of our paper we arranged to subject these concentric cylinders to 60-cycle voltage. In so doing all essentials were made to correspond to those present in the high-frequency work, *i.e.*, the neutral of the single-phase 60-cycle source was grounded, while the "neutral"-connected outer eleven-inch cylinders were left isolated. They were shunted with the sphere gap set to stop any possible transient

over-voltages. Thus arranged, the sphere gap acted in agreement with voltages determined by transformer ratios and voltmeter. The concentric cylinders discharged at voltages all the way from 80 to 100 kilovolts. The lower and higher values occurred correspondingly when the voltage was raised slowly and rapidly. Using one pair of cylinders only, the outer one grounded, the discharge voltages ranged from 40 to 50 kilovolts. The equipment was then dismantled and the seven-inch cylinders were mounted in a cross and separated so as to form a gap between them of three inches; so arranged, 157 kilovolts were required to discharge between them. It seems to us that the free ionization in this case is present in the tarnished and dust-coated surfaces of these cylinders, and from there is worked into a line-up forming local corona through the two-inch zones of well-protected air under the forces of the electric field, thereby starting a disturbance that finishes in a heavy spark, *i.e.*, in a transient discharge, or otherwise, in an actual arcing short circuit. The discharging voltages were lower when the tests were started and gradually rose as the reapplications of high voltage were continued, indicating a sort of cleaning-up process.

In the second experience it was found that when using a seven-inch sphere gap of two inches or thereabouts, the high-frequency discharge would take place by the shortest path between the spheres at 93 kilovolts. When a lower voltage was applied and a slight disturbance created at one of the surfaces of the opposing spheres by touching it with a piece of hard rubber, a discharge immediately occurred. It would be started by a spark of charging current from the sphere to the hard rubber. Discharges, a foot and more in length, would be made to pass from the rearward surface of one sphere to the corresponding rearward surface of the other at 85 kilovolts, in the general direction of the lines of force, by bringing to the surface of the sphere from the rear a three-quarter-inch hard rubber rod.

Mr. Mahood recommends that the Poulsen oscillating arc used for sphere gap voltmeter calibration be replaced by "the best oscillating arcs constructed and specially designed for stability purposes" giving only "*two per cent* variation in amplitude at 133,000 cycles." Such arcs, while steady, are entirely lacking in duty capacity. A maximum of 1500 kilovolt-amperes of reactive power was employed for the high-frequency sphere gap work, while a few hundred volt-amperes suffice for standardizing radio receiving apparatus—accomplished readily enough with such light-duty constant arcs. Mr. Mahood confuses the duties of the ammeters in the circuit of the concentric condensers and the potential cyclograph. The former and not the latter read the r.m.s. of the existing potential. The cyclograph gave a continuous vision of the procession of potential oscillations in instantaneous detail. The same speaker makes the suggestion that pure undamped waves were not used in our work because under his own assumption the decrement (for

damped waves) was 0.02. The suggestion can not be taken seriously. The cathode ray cyclograph established beyond all reasonable doubt that the oscillating potentials were formed continuously and undamped. These are merely efforts to find near-by evidence to support the theory that the action of the sphere gap voltmeter is independent of the frequency of the applied voltage.

The sphere gap discharge voltages were not altered by the use of the safety resistance rods at 123,000 cycles. They were abandoned at higher frequencies, as stated in the paper, because the resistances that would limit sufficiently the rush of continuous current that followed a discharge across the sphere gaps would consume an undue amount of power, limiting or preventing the generation of voltage in the oscillating circuit.

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ENGINEERING DATA RELATING TO HIGH-TENSION TRANSMISSION SYSTEMS

SUB-COMMITTEE REPORT PREPARED BY THE CHAIRMAN

THE present report is an analysis of the engineering data received from 25 power companies, operating high-tension transmission systems, in answer to a printed list of questions prepared by the High-Tension Transmission Committee of the year 1912-1913, and sent by that committee to 105 power companies operating at 25,000 volts and over.

The present Engineering Data Sub-Committee has received the replies to these questions and has analyzed the data therein contained as hereinafter presented. In making this analysis, the main purpose has been to present, as far as feasible, the data having general interest in a form which shall at the same time be compact and easy of assimilation. A considerable part of the data which is statistical has been consolidated in tables which show in parallel columns for the several reporting companies various items of interest returned. A second portion of the data received could be presented more intelligbly under the various topical headings to which it related, and has been so offered. As a matter of convenience the reporting companies have been listed, with a brief statement as to the character of each plant and an abbreviation of the title assigned to it for the purpose of identification, to avoid the reprinting of the full names of companies a large number of times in the body of the report. In addition to the listed data, the companies have furnished a large number of blue-prints, drawings and maps, many of which contain valuable designs and constructional details. Much of this material has been reproduced in the form of cuts at the end of the report. To facilitate examination and to economize space most of this matter has been redrawn to present the salient information free from non-significant detail. Where useful, dimensions and similar data have been given in the reproduced drawings.

The original reports returned from the companies will be on file at Institute headquarters and open to the inspection of any Institute member, should further details be desired. Furthermore, in the list of companies below are given the name and address of the person by whom the report was submitted, and it is very possible that further information with regard to the apparatus or practise of that company referred to in this report, could be obtained by direct application to such person.

Neither the Engineering Data Sub-Committee nor the Institute assumes any responsibility for the correctness of the information here reported. The sub-committee has endeavored, however, to give a clear and fair report of the information offered.

The sub-committee wishes to express its thanks and appreciation for the freedom with which companies have reported and to acknowledge its obligation for the large amount of personal attention and thought which was required on the part of reporting engineers to answer the very comprehensive list of questions that was submitted. Certain reports in particular should receive especial mention as showing an unexpected amount of painstaking description and discussion of some of the most important and delicate problems confronting high-tension transmission engineers. The sub-committee believes that the comparison of experiences and practise herein set forth cannot fail to be of much value to the profession and will certainly be of great assistance to those engineers having high-tension plants to establish who have not the time and opportunity for the extended research that is necessary in the case of plants of the first magnitude.

LIST OF REPORTING COMPANIES

100,000-VOLT GROUP

Mississippi River Power Co., (Miss. P.) Keokuk, Ia.—St. Louis, Mo.
Stone & Webster Eng. Corporation.

The data returned cover a double trunk line electrification. It represents the very heaviest type of large capacity transmission line and is recently completed. The report is a most valuable one.

Great Western Power Co., (Gt. W'n. P.) California
P. T. Hanscom, Asst. to the President, 233 Post St., San Francisco, Cal.

The data returned cover a large capacity trunk line electrification across the state of California from the Sierra Nevada Mountains to the neighborhood of San Francisco. A very valuable report. This plant has been operating several years.

YADKIN RIVER POWER CO., (Yad. R. P.) North Carolina
R. J. McClelland, Chief Engineer, Electric Bond & Share Co., 71 Broadway, New York.

The data returned cover a trunk line electrification of medium capacity, connecting a large hydroelectric development supplementary to a previously existing system, and is but recently finished. A valuable report.

PACIFIC GAS & ELECTRIC COMPANY, (Pac. G. &. E.) Central California. San Francisco.

This is one of the largest, oldest and most diversified companies in the country.

CHILE EXPLORATION CO., (Ch. Ex.) Chile.
Percy H. Thomas, Consulting Electrical Engineer, 2 Rector St., New York.

This line, which is not yet in operation, is a large capacity trunk line for supplying power for operating a very large copper mining development, including the electrical refining of the metal at the mine. It is notable as transmitting power from a power-house at the ocean to a mine at an elevation of 9000 feet.

NOTE. One company ("X") did not wish its name used. It is a large system in a bad lightning district. It has a very large, widely distributed power load.

85,000-VOLT GROUP

MEXICAN LIGHT & POWER CO., (Mex. L. & P.) Necaxa to the City of Mexico.
C. B. Graves, General Manager, Apartado 124, bis., Mexico, D.F.

The data returned cover a number of transmission lines in a very large system which collects power from a number of power stations and distributes it over a wide range of territory. This plant has been operating for a number of years. A very full and useful report.

APPALACHIAN POWER CO., (Ap. P.) Bluefields, W.Va.
H. W. Buck, Viele, Blackwell & Buck, 49 Wall St., New York.

This plant, which is very modern, illustrates the problem of the distribution of power in moderate quantities to a distributed load. It has been operating but a short time. A valuable report.

SOUTHERN SIERRAS POWER CO., (Sou. S. P.) Southern part of California.
R. G. Manifold, Engineer, Riverside, Cal.

The data returned cover a high-voltage construction for an extremely long-distance transmission operated in conjunction with a previously existing system of large extent. It operates at present at a lower voltage than ultimately contemplated. A valuable report.

PENNSYLVANIA WATER & POWER CO., (Pa. W. &. P.) Holtwood to City of Baltimore.
J. A. Walls, Chief Engineer, Baltimore, Md.

The data returned cover a heavy trunk line electrification in a very difficult lightning district, receiving power from the well-known Susque-

hanna River hydroelectric development. The engineering of this line has been particularly carefully worked out and the report is especially full and valuable.

60,000-VOLT GROUP

WASHINGTON WATER POWER CO., (Wash. W.P.) Washington.
O. F. Uhden, Chief Engineer, Spokane, Wash.

The data returned cover a new trunk tower transmission line and also standard 60,000-volt wood pole construction. This is part of a very large and widely distributed system. A valuable report.

TORONTO POWER CO., (Tor. P.) Ontario. Canada.
F. G. Clark, Chief Engineer, Toronto, Ont., Canada.

This is a large-capacity trunk line through a bad lightning district, from Niagara Falls to Toronto. A good report.

SAN JOAQUIN LIGHT & POWER CORP., (San. J. L. & P.) California.
Lloyd N. Pearl, General Superintendent, Fresno, Cal.

This is a widely spread distribution system using wooden poles in the Southern Central district of California. A particularly dry climate.

NIAGARA, LOCKPORT & ONTARIO POWER CO., (Niag. L. & O.P.) Western New York.
L. C. Nicholson, Marine Bank Building, Buffalo, N.Y.

This is a double trunk line through the western part of New York State in a very bad lightning district. This plant has been in operation a number of years and its engineering has been very carefully studied. A valuable report.

PORTLAND RAILWAY, LIGHT & POWER CO., (Port. R.L. & P.) Oregon.
O. B. Coldwell, General Superintendent, Broadway, Portland, Ore.

The data returned cover some of the more modern construction of an extensive generating and distribution system of large capacity. A valuable report.

SOUTHERN CALIFORNIA EDISON CO., (Sou. C.E.) California.
J. A. Lighthipe, Los Angeles, Cal.

The data returned cover a portion of a large and well-known system feeding into Los Angeles, Cal.

CHIPPEWA VALLEY RAILWAY, LIGHT & POWER CO., (Ch'a. V.R.L. & P.) Wisconsin.
Eau Claire, Wis.

WESTERN STATES GAS & ELECTRIC CO., (W. St's. G. & E.) California.
Stockton, Cal.

The data returned cover an extensive distribution system in Central California. Wood-pole type of construction.

PUGET SOUND TRACTION, LIGHT & POWER CO. (P. S. T. L. & P.) Wash.
John Harisberger, M. T. Crawford, S. C. Lindsay, Seattle, Wash.

The data returned cover a large generating distribution system around Seattle, with modern transmission lines. A portion of the plant has been in operation for a number of years.

CITY OF SEATTLE LTG. DEPT. (City S. L. Dpt.) J. D. Ross., Seattle, Wash.

Name of Company	Line Voltage	Frequency	Length—Miles	General Type.	Elevation—feet.	Arrangement Conductors and Ground Wires.	Neutral Grounded
	1	2	3	4	5	6	7
[illegible]	110,000	25	144	2 circuit steel towers	500 +	Conductors vertical ground wire at peak.	Yes, at Keokuk only no resistance
[illegible]	100,000	60	154	2 circuit steel towers	0 to 1500	Conductors vertical ground wire at peak.	No
[illegible]	100,000	60	96	2 circuit steel towers	200	Conductors vertical ground wire at peak.	Yes, one point no resistance
[illegible]	110,000	50	57	One circuit steel towers	0 to 9800	Two ground wires 3 horizontal conductors	
[illegible]	100,000 60,000	60	109.5 1260 total		0 to 4000		At generating and many substations, no resistance
[illegible]	88,000	60	510 total	2 circuit steel towers.	700 to 900	Conductors vertical ground wire at peak.	88,000 volt line grounded at power houses.
[illegible]	88,000	50	95.3+ 75.3+ 29.4 = 200	2 circuit steel towers pin type insulators.	2950 to 10,800	Two delta side by side ground wire between.	At seven points, no resistance
[illegible]	88,000	60	240 total	Wooden pole suspension insulators.	2000	Delta and wishbone crossarm.	No
[illegible]	55,000 67,000 140,000	60	238	2 circuit steel tower	1000 to 4500	3 wires on each side tower, middle 5' beyond top and bottom wires, one ground wire at peak	At each hydroelectric station, no resistance
[illegible]	70,000	25	40	2 circuit steel tower	35 to 690	Conductors vertical ground wire at peak. Note 23.	At power house only one trans. on each circuit.
[illegible] (Power Line)	60,000	60	28	2 circuit steel tower	1300 to 2450	Conductors vertical ground wire on peak.	At generating stations and substation no resistance.
[illegible] (Pole Line)	60,000	60	580	Wood pole pin type insulator.	1300 to 4800	Delta and horizontal.	At generating sta. and many substations no resistance.
[illegible]	60,000	25	80	2 circuit steel tower	750 to 300	Two deltas side by side Delta btn.	No
[illegible]	60,000 60,000	60	650 total	Wooden pole pin type insulators	300	One circuit pole top and crossarm.	Yes, at all power houses and substations
[illegible]	60,000	25	180	One circuit steel tower one circuit wood.		Star connected at generating station, neutral grounded through 1000 ohms.	Yes, at generating only 1000 ohms [illegible]
[illegible]	57,100 and 33,000	33 and 60	158	2 circuit steel towers and wooden poles.	400 to 50	Conductors vertical one side only installed ground wire in peak	At each generating station and substation 60 cycle 57,100 volt line
[illegible]	[illegible],000	50					All Transf. Neutral grounded, no resistance
[illegible]	60,000	60	36.4	One circuit wooden pole.	50 to 1000 ft.	Delta with wire at pole top.	Yes at one point, no resistance
[illegible]	60,000	60	119		800		No
[illegible]	60,000	60	200 total	One circuit wooden pole.		Delta with wire at top of pole.	Yes, no resistance
[illegible]	[illegible],000	60	465 total	1-circuit wooden poles. 2-circuit steel towers.	0 to 900	1-circuit delta. 2-circuit vertical.	No, all delta
[illegible]	[illegible],000	60	40	2 circuit steel towers	4500	Vertical planes.	At each power house no resistance
[illegible]	24,000	25	16	2 circuit steel poles	600	Two deltas on steel crossarms.	No
[illegible]	60,000	[illegible]	[illegible]	[illegible] wooden poles	[illegible]	Delta with wire on top of pole	At each power house no resistance
[illegible]	[illegible]	[illegible]	[illegible]	2 circuit wooden poles		Two deltas side by side	No

Type of Tower	Character of Foundations	Height Lowest Conductor above ground in feet	Horizontal Spacing of Conductors	Vertical Spacing of Conductors	Spacing of Ground wires from Conductors, Horizontal and Vertical	Clearance Conductors to tower—no wind.	Clearance Conductor to Tower, max. wind.	[illegible]
8	9	10	11	12	13	14	15	[illegible]
Square top section on pyramid base		50	17.9 18.8 19.9	10	9½ hori. 3½ vert.	6½		[illegible]
Square top section on pyramid base				10				[illegible]
Square top section on pyramid base		45	15½	9	7½ hori. 9½ vert.			[illegible]
Two vertical A frames and cross bracing	Standard, earth foundation single stubs and grillages	40	13		6½ hori. 7 vert.	6½		[illegible]
								[illegible]
Steel towers 72 ft. high. Square top section on pyramid base	Earth stubs.	25	18	10				[illegible]
Two vertical A frames and cross bracing.		40½	6	5½	3 hori. 6½ vert.	2½		[illegible]
Wood pole.		28	8½	8	4½ hori. 5 vert.	4		[illegible]
Square top section on pyramid base.	Earth stubs. Concrete. Note 24.	44	16½ middle 26½	10	8½ hori. 6 vert.	5½		[illegible]
Square top section on pyramid base		44	15½	7	3 hori. 4½ vert.	5½		800
Square top section on pyramid base.	Single stub and grillage.	51	17½ 26½ 19 5/6	7	8½ hori. 5½ vert.	6½		750
Wood pole.					2½ hori. 3 + 6 vert.			[illegible]
	7 ft. angle legs with foot piece Note 21.	40	6	6	3 hori. 12 vert.			400
Wood pole			9	6	None.			[illegible]
Steel pipe-motor type Wooden "A" frame	Concrete for steel towers.	49	7	6	None			[illegible]
Square top section on pyramid base	7 ft. stub and footing 2 ft. square, usually no concrete	48	11	6	5½ hori. 4 vert.	4		500
								700
Wood pole.			7	6	None			[illegible]
Steel Wood								600 250
Wood pole			6	5½	None			175 [illegible]
Square 4 leg. Square 3 leg.	Concrete	30	6 to 8	7				175 450
Steel towers 60 ft. high 45 ft. wood poles	Concrete	45 at tower	12	6	3 ft. vert.	5 ft.	2½ ft.	600 150
6 in. pipe trussed and	Concrete	40	3	2-7/12	18 in. hori. 3 ft. vert.	16 in.		300 ft.
Wood pole			5½	4-7/12	None			300

2 Gt. Wn. P.		Use strain insulators as usual.	Grounded by reinforcing in their bases.	
3 Yad. R. P.		Dead End Towers.	Only by footing.	Separate formers.
4 Ch. Ex.		Special angle Towers above 3°—smaller angles ignored.	Ordinarily no concrete used.	
5 Pac. G. & E.	20°F to 100°F		Not specially	Auto tra
6 X	0° to 38°C.	Angles up to 30° split angle on one tower, above 30° divide equally on two towers.	Through legs which extend into earth	Separate formers.
7 Mex. L. & P.		See Note 1.	Not specially grounded, set in cement.	
8 Ap. P.			Ground wire down pole put in a coil near bottom of pole.	
9 Sou. S. P.		Up to 2° ignored 2° to 8° Std. tower deadened 8° to 17°—1 guy 17° to 22° —2 guys over 22° heavy tower on vertical angles over 4°—20 ft. and Std. spans dead End.	No special provision for grounding.	Separate formers.
10 Pa. W. & P.		All horizontal and all all heavy vertical angles on anchor towers.	Std. towers no concrete footing, anchor towers in concrete grounded by rods 5 ft. below foundations.	
11 Wash. W. P. (Steel Tower Line.)	30 to +120° F.		Steel towers grounded through footings only.	
12 Wash. W. P. (Wooden Pole Line.)	30 to +120° F.	Grounded curved guards on inside of curve wooden poles.		
13 Tor. P.	—20 to +110°F	Up to 15° on Std. towers, over 15° special angle towers.	In dry location copper ribbons extending 8 to 12 ft. into ground.	
14 San J. L. & P.	20 to 110° F	Note 2.	No ground wire on poles.	Separate formers
15 Niag. L & O. P.	—10 to 110°F.	Use self sustained or guyed towers at ends of tangents, if necessary for clearance, third tower added	Galvanized iron strap 3" x 1/8 and 4 ft. under ground buried in coke.	Separate formers
16 Port. R. L. & P.	0 to 100°F.	Angles to 20° without special construction.	Special ground plate on some of steel towers.	Separate formers
17 Sou. C.E.	30 to 100°F.	Double construction on heavy angles.	No special precautions.	Separate formers
18 Cty S. L. Dpt.	0 to 100°F.	Double construction maximum deflection at single point of support is 30°		
19 Ch'a. V. R. L. & P.			Grounded through 1½ in. iron pipe but only with concrete footings.	In one formers.
20 We. St's. G. & E.			1 ground rod at each tower.	Separate formers.
21 Pug. S. T. L. & P.	+20 to +90°F.	Square	Through foundations only.	Separate formers.
22 Ch. L. & P.	20	3 sets strain clamps on [illegible] structure	Separate [illegible] grounds and [illegible]	[illegible]

						[illegible]
	17,000 volts, 20,000 Kw. per line P. F. 96 volts at power house 107,200.	Yes, on river crossings; satisfactory.			40,000	11,000 [illegible]
[illegible] Transfer-	10%—5000 Kw. at receiving end 80% P. F., 87 miles.	Copper clad extra long spans, satisfactory.	10,000 pull at center, either longitudinally or transverse.		24,000 2,500	[illegible]
	10% with 25,000 Kw. delivered. P. F. 99 lagging.		8100 lbs. longitudinal on one A frame with 6000 lbs. transverse simultaneously.	All wires cut on angle towers.	None.	[illegible]
[illegible]		Yes, in use short time.			9 stations 400 to 25,000.	[illegible]
[illegible] Transfor-		Yes, on telephone satisfactory.	2 wires cut maximum load conditions.	3 wires cut maximum load conditions on anchor towers.	24,000 24,000 18,000 10,000 8,000 6,600 2,500 1,200	[illegible]
[illegible]		No.	Fail when four of the six wires are cut.	53 ft. towers on tangent guyed stand 6 wires cut.	12 plants 85,000 total	3 [illegible]
		No.	1 conductor broken.	Dead end towers all conductors broken.	20,000 9,000	[illegible]
[illegible] Trans-		No.	16,000 lbs. at center of crossarms will not stand with all wires cut.	Dead end towers 24,000 lbs at center.	6,000 6,000 6,000 2,000 1,500	[illegible]
	10,000 volts drop from 70,000 volts 60,000 Kw—2 lines 95% P. F. delivered, 300 amps, 40 miles.		One half cables cut, 15,000 lbs. horizontally across or with line.	All cables cut includ. ground wire. 30,000 lbs at center across or with line.	72,000	[illegible]
			Note 16.		8,800 11,250 20,500	[illegible]
	Some lines 0 to 5000.	Yes, satisfactory				
	20% at 15,000 Kw. 85% P .F.		One broken cable 2700 lbs. with reasonable factor of safety.	Anchor and angle towers all conductors broken.	102,000 at Niagara	12,000 [illegible] Toronto 6,000 D. C.
[illegible] trans-	15%, load distributed at 3 points along line.	No.	Wooden pole, 2 conductors broken.		16,000 6,000 1,500 2,000	15,000
[illegible] trans-		No.	Single circuit strain towers, all three wires. Other towers one wire.		75,000 Niagara	[illegible]
[illegible]		No.	Note 18.		7,200 14,250 9,900 11,250	12,[illegible] 1,[illegible] [illegible] [illegible]
[illegible]		No.	One wire cut.		3,000 1,000 3,250 650 500 20,000	16,[illegible] 47,[illegible]
	3420 volts with 9000 Kw. delivered at 95% P. F. one line.	No.	All conductors cut on one side.		15,000	N[illegible]
[illegible] auto-trans-	6000 volts for 3500 Kw.—25 miles, 75% P. F.	No.			5,000 1,200 600 2,000	
[illegible]					3,000	[illegible]
[illegible]	Not over 10 per cent.	Yes, on telephone; satisfactory.			20,000 9,000 11,500 15,000	12,[illegible] [illegible] [illegible]

III

	Name of Company	Conductor Size and Material	Elastic Limit Assumed per Sq. In.	Ultimate Strength Assumed per Sq. In.	[illegible]
1	Miss. P.	19 Std. hard drawn copper 300,000 cm.	30,000	60,000	[illegible]
2	Gt. Wn. P.	No. 000—7 Std. hard drawn copper.			
3	Yad. R. P.	No. 0, 6 Std. hard drawn copper, no core.	25,000	57,500 by test.	[illegible]
4	Ch. Ex.	No. 000 copper.	34,000 by test	6,900 by test.	[illegible]
5	Pac. G. & E.	All sizes copper and aluminum.			
6	X	88,000 { No. 0 copper; No. 00 copper; equiv. 7 std alum	26,800	48,000	[illegible]
7	Mex. L. & P.	No. 000 copper, 6 strand hemp center.	35,000 38,000 by test.	55,000; by Test. No. 0 50,600 No. 000 53,100	[illegible]
8	Ap. P.	No. 0, 7 Std Alum.	14,000 by test 16,000.		[illegible]
9	Sou. S. P.	8 std. alum. outside and 1 steel core, each 35,235 cm.	Al. 14,000 St. 130,000	Steel 214,000	Al. [illegible] St. [illegible]
10	Pa. W. & P.	19 Std. alum. 300,000 cm.	15,700 by test.	25,500 by test.	2,1[illegible] by [illegible]
11	Wash. W. P. (Steel Tower Line)	270,000 cm. alum.		(Note 16)	
12	Wash. W. P. (Wooden Pole Line)				
13	Tor. P.	198,000 cm. hard drawn copper, 6 std. hemp core.	29,000	47,800	[illegible]
14	San J. L & P.	No. 0 copper No. 000 No. 0000 } alum			
15	Niag. L. & O. P.	642,000 cm.—19 std. 428,000 cm.—19 std. 214,000 cm.—7 std. all aluminum No. 4 copper 7 std.	12,500 30,000	25,000 58,000	[illegible]
16	Port. R. L. & P.	420,000 cm.—19 std. hard drawn copper on steel tower lines.	33,000	60,000	[illegible]
17	Sou. C. E.	No 0000 copper			[illegible]
18	Cty. S. L. Dpt.	No. 0000—7 std. hard drawn copper.	45,000	60,000	[illegible]
19	Cha. V. R. L. & P.	No. 4 hard drawn solid copper.			
20	We. St's G. & E.	No. 1 alum. No. 4 copper.			
21	Pug. S. T. L. & P.	No. 4 solid; No. 0000—19 strand medium hard drawn copper; No. 00 and 0000—7 std. alum.	30,000 copper. 12,000 alum.	55,000 copper; 25,000 alum.	[illegible]
22	Ut. L. & R.	No. 0 hard drawn stranded, No. 1 solid.	35,000	60,000	
23	C. N. P.	500,000 cm. std. al.; 19 strands copper clad No. 10 on long span.	14,000, by test on strands 15000	25,000	
		No. 2 copper No. 6 [illegible]		34,000	

Modulus of Elasticity	Maximum Working Strength per Sq. In.	Size and Material of Ground Wire	Elastic Limit Assumed per Sq. In.	Ultimate Strength Assumed per Sq. In.	Modulus of Elasticity	Maximum Working Strength per Sq. In.	Range of Temperature Assumed	Ice and Sleet assumed	
		½ in. "Siemens Martin" galv. steel std.	50,000	75,000	29 x 10^6		—24.5 C to 41.5 C	½ in. on radius at 15°C	
x 10⁶	25,500	½ in. "Siemens Martin" galv. Steel strand.		For the cable 6800, by test 8000.				½ in. on radius.	
x 10⁶ by	22,000	½ in. "Siemens Martin" galv. steel strand.	4000 by test	8,900 by test	29 x 10^6		—5°C to 55°C.	None.	
							20°F to 100°F		
x 10⁶		½ in. "Siemens Martin."					0°F to 100°F.	½ in on radius.	
5 x 10⁶ x 10⁶ by	Factor of safety 3 and 2.		100,000		22 x 10^6		0°C to 50°C.	No. sleet	
7 x 10⁶			30,000 by test.		25 x 10^6			½ in. on radius	
8 x 10⁶ 20 x 10⁶		½ in. "Siemens Martin" galv. steel strand.		For the cable 6800.			0° to 130°F.	½ in. on radius	
2.16 x 10⁶ test.		½ in. "Siemens Martin" galv. steel strand.		53,000, for the cable 6800.			—25° C to 50°C.	½ in. on radius	
		½ in. "Siemens Martin" galv. steel strand.					—30°F to 120° F	0.8 lbs. per ft. for all sizes conductors.	
		½ and ¼ in. "Siemens Martin' galv. strand.					—30 to + 120° F.	0.8 lb. per ft. for all sizes conductors.	
x 10⁶		½ in. "Siemens Martin" galv. steel strand.	For cable 5750	For the cable 9600.			—20° to 110°F	½ in. on radius	
	27,500 12,000 12,000	None.					0° to 50°C.	No ice	
x 10⁶ x 10⁶		None					—40° to 110°F	½ in. on radius.	
		½ in. "Siemens Martin" galv. steel strand.	For cable 3,400.	For the cable 6800.	27 x 10^6		—25° to 125°F	½ in. on radius.	
x 10⁶							20 to 120°F.	No ice.	
x 10⁶		None.					0° to 100°F	½ in. on radius.	
10⁶ x 10⁶ 6 x 10⁶							0° to 100° F	No ice	
	8,000	5/16 in. galv. steel strand	40, 000	70,000			—20° to 110°F	½ in. on radius.	
9 x 10⁶	6000	5/16 in. galv. steel wire	30,000, by test on strand 40,000	50,000, by test on strand 80,000	29 x 10^6		0—90F		

IV	Name of Company	Are outdoor Type Transformers or oil switches or sub-stations used.	Are Tanks of outdoor Transformers or Electrolytic arresters painted	Is oil tested regularly and treated as necessary
1	Miss. P.	Yes 11,000 volt transformers.	Painted white	
2	Gt. Wn. P.	Yes transformers on 22,000 volts	No, use No. 12 oil in Transformer	
3	Yad. R. P.	Yes, all.	Painted white	All oil tested regularly and treated as necessary
4	Ch. Ex.	No.		Not yet operating
5	Pac. G. & E.	Yes.		No
6	X	Yes		Yes
7	Mex. L. & P.	None		
8	Ap. P.	Yes		
9	Sou. S. P.	All substations outdoors.	Transf. no; elect. arrest. tanks painted white	
10	Pa. W. & P.			
11	Wash. W. P. (Steel Tower Line)			No
12	Wash. W. P. (Wooden Pole Line)	Substations and transf., no oil switches.	Paint tanks white	No
13	Tor. P.	Substations and transf., no oil switches	Painted white, wooden covers used in some cases	
14	San J. L. & P.			
15	Niag. L. & O. P.	Yes, switches	No protection	Yes, oil from tank has been found [illegible]
16	Port. R. L. & P.	Substations and trans., no oil switches.	No protection.	No
17	Sou. C. C.			
18	Cty S. L. Dpt.			
19	Ch'a V. R. & L. P.	Yes, no oil switches.	Painted white	No
20	We. St's G. & E.			
21	Pug. S. T. L. & P.	No		
22	Ut. L. & P.	No	None	No
23	C. N. P.			
24	Mt. Whit. P. & E.	Yes	Painted aluminum paint.	No

TABLE IV.

Are Current limiting reactances used? If so, how?	Is telephone lines same poles or Towers	How far are telephone wires separated from line conductors	How far are telephone wires spaced apart	Size and Material of Telephone Wire	How is Telephone Line Transposed	How is Power Line Transposed	How are users of telephone Line Protected
Note 12 Reactances in groups of generators	Separate wooden poles	68½ ft.	8 in.	No. 8 copper	Every 625 ft.	None	Note 8.
No	Yes	20 ft.	12 in.	No. 8 B. & S. copper	Each tower	Yes	Fuses and lightning arrest, insulating transf. Insulating stools
No	Separate poles	500 ft. to 1 mile	16 in.	No. 8 copper clad	Every 8th pole	Two times	Insulating stools, insulating transf.
No	No	180 ft.		No. 10 copper		Two complete transpositions	
Yes	Yes		12 in.		Separate insulators wherever possible	About every 8 miles	Insulating transf. and stools
No	Separate poles	60 ft.	32 in.	No. 10 galv. iron, No. 8 copper clad	Every third pole	Not transposed	Insulated stools
	1 Circuit yes, 1 circuit on separate poles	11 ft.	30 in.	No. 10 solid copper	Every 500 ft.	17 times Necaxa to Mexico City	
No	Yes	10 ft.	8 in.	No. 8 B. & S. steel.	Every other pole	None	Insulating transformer
No	Separate poles	Average one mile away	36 in.	No. 6. medium hard drawn copper	Every half mile	3 complete transpositions	No special precautions
Yes, Note 13	Separate wooden poles	25 ft. from tel. poles to towers	12 in.	No. 12 B. & S. No. 9 B. & S hard drawn copper	Note 9	2-120° transpositions	Lightning arrest and fuses insulating transf. at Baltimore
No	No		12 in.	No. 9 iron.	Every high tension transposition and between	Note 10	Insulating transf.
No	Yes	4 to 7 ft.	24 and 30 in.	No. 9 iron. No. 12 iron. No. 8 copper.	Every high tension transposition and between.	Note 10	Insulating transf.
No. Note 14, but are considering their use	Yes, five miles only	20 ft.		No. 10 solid copper	Every 4th pole	3 complete transpositions	Drainage coils vacuum arrest., insulating transf.
No	Yes	12 ft.	3 ft.	No. 6 hard drawn copper	Every half mile	None	Note 11.
No	Yes, and on separate poles	9 ft. or 15 to 200 ft. away.		No. 10 N.B.S. copper and No. 8 B. W. G. galv. iron.	Every tower	None	Drainage coils and insulating transformer
No	Yes	10 to 12 ft.	30 in.	No. 10 copper clad No. 9 iron.	Every 3 to 5 spans.	None	Insulating transf.
Yes, Note 15	Yes	6 ft.		No. 10 copper	Every tower	None	Carbon block arrest and wooden booths
No	Yes	15 ft.	6 ft.	No. 12 B. W. G. Iron. No. 11 B. & S. Copper	Every 3200 ft.	Every 12,800 ft.	Insulating transf. and booths.
No		6 ft.	3 ft	No. 12 B. & S.	Every 500 ft.	Only 1 line 3 times a mile	Insulating transf.
No	Yes	15 ft.	26 in.	No. 12 copper, copper clad steel.	Every 750 ft.	Every 5 miles	Transformers, grounded gaps, and stools
No	Yes	12 ft.	30 in.	No. 9 galv. iron	Every tower	Every 1½ to 3 miles	Insulating transf.
No	Yes	7 ft.	4 ft.	No. 10 iron, No. 12 copper	Every 3rd pole	2 Complete in 16 miles	Insulating platform
No	Yes	5 ft.	16 in.	No. 12 E. B. B. steel		None	Insulating transf.
No	Yes	[illegible] ft.	12 in.	No. 12 copper	Every [illegible]		

Name of Company	Type and Maker Standard Insulator	Type and Maker Strain Insulator	Test of Standard Insulator Dry	Test of Standard Insulator Wet
1 Miss. P.	String-7-Ohio Brass Porcelain Dwg. 8650	String-8-O.B. Porcelain Dwg. 8650.	440,000	330,000
2 Ct. Wn. P.	String-5 R. Thomas No. 1053, Porcelain	R. Th. 1063, 1060, O.B. L.-371, L-620. Locke273	70,000 on each disc.	48,000 on each disc.
3 Yad. R. P.	String-6 R. Th. 1113 Porcelain	R. Th. 1113, Porcelain	87,000 volts on each disc.	
4 Ch. Ex.	Locke 3326	Locke 3326	435,000 flash over—individual discs 91,000	300,000 volts.
5 Pac. G. & E.	All kinds.	Largely O. B. St andard	Flashover	
6 X	String 4 Locke 2298 Thomas 2052	String 5, Locke 2298 Thomas 2052.	95,000 volts for 10 min. per Disc, mech test 8000 lbs.	45,000 for 5 min. per disc mech, test 8000 lbs.
7 Mex. L. & P.	R. Th. 2 Petticoat 17½" x 21" and 3 Petticoat 18½" x 21" Porcelain.	Pin type.		120,000 with clear water 55,000 with alkaline sand on petticoats.
8 Ap. P.	String 4 R. Th. 1053 with hood Porcelain	String-5-R. Th. 1053 with hood Porcelain.	90 % of arc over voltage 5 for minutes	
9 Sou. B. P.	String 6, Locke 2036 O. B. 10567, Porcelain	Locke 2036, O. B. 10567 Porcelain		
10 Pa. W. & P.	String 5-O. B. 10566 slate. Note 22 Porcelain.	String 6 O. B. 10567	Strings 5 units 310,000, discs 65,000-3 min. also 4000 lbs., ultimate strength 8500 lbs.	String of 5 units [illegible]
11 Wash. W. P. (Steel Tower Line)	String 4-0 O. B. 10566	String 5 O. B. 10566	Discs 85,000	Discs 50,000
12 Wash. W. P. (Wooden Pole Line)	Locke 341 and 351, O. B. 9418; R. Thomas 60,000 volt Porcelain.	5—O. B. 10566	Pin Type 180,000	Pin Type 118,000
13 Tor. P.	R. Thomas 3037 pin type Porcelain.	String 4—Locke 2036 Porcelain.	Note 17	Twice line voltage on complete insulator.
14 San. J. L. & P.	Locke 360 Pgh. H. V. No. 189, Brown Porcelain	String 2—Locke 273 3—R. Th 1060.	180,000 volts five minutes	
15 Niag. L. & O. P. Co.	O. B. 7742, Locke 358 Porcelain.	Practically none used.	220,000	140,000
16 Port. R. L. & P.	String 3- O.B. 10566 Porcelain.	String 4-O. B. 10566	4000 lbs. mech. Disc. 90,000-105,000 flashover.	
17 Sou. C. E.			Test on shell 60,000 & 50,000, assembled 150,000	
18 Cty. S. L. Dpt.	Thomas 3037—3 part insulator.		180,000 volts	120,000 volts.
19 Ch's. V. R. L. & P.	O. B. 9418	String 3-O. B. 10567		132,000
20 We. St's. G. & E.	Locke 351 Redlands type Porcelain	String 4, Locke 2335		
21 Eng. S. T. L. & P.	S. & W. No. 1.	Porcelain link type.	120,000 volts.	100,000 volts
22 [illegible]	[illegible]	[illegible]	On disc 4000 lbs., 75,000 volts	[illegible]

[illegible] Insulators Dry	Test of Strain Insulators Wet	Type and Number of Arresters on System	Setting of Gaps	Do they Always discharge when one line wire is grounded	How often are [illegible] charged, is through resistance?	[illegible]
[illegible]	330,000	Electrolytic, 5-3 pole on each line	Minimum gap 8 in.		Daily, through resistance	[illegible]
[illegible] volts on each disc.	58,000 volts on each disc	Electrolytic, cut out of service no lightning				
[illegible]			10 to 15% over normal potential	No	Twice daily, resistance being installed.	[illegible]
[illegible] stops for suspension [illegible] at or just below [illegible]		2-sets horn gaps with resistance				
[illegible]		Few plain horn gaps	50% to 100% over normal potential	No		[illegible]
[illegible] for 10 min.	45,000 for 5 min. per disc.	27 Al cell electrolytic	50% over normal potential	Yes	Every twentyfour hours, no resistance	[illegible]
[illegible]		Electrolytic, 180 cells at 7 stations.	Just above maximum voltage. See note 3.	Yes	Daily, no resistance	[illegible]
[illegible] of arc over voltage [illegible]		Electrolytic, 4 total	125% of line voltage	Yes	Daily no resistance	[illegible]
[illegible]		Electrolytic, 4-3 pole	120% of line voltage		3 times daily, in hot weather, 2 times in cold, no resistance	[illegible]
[illegible] of 3 units 280,000 [illegible] 50,000-3 minutes [illegible] dry, dry, strength [illegible] lbs.	String of 6 units 250,000	Electrolytic, 2-3 pole	4½ in. gap.	Yes	Daily, no resistance yet, but resistance will now be used	[illegible]
[illegible] 85,000	Discs 59,000	40 Electrolytic on total system	Set where normal voltage cease to start an arc.	Yes	Daily, 4400 ohms per leg on some sets.	[illegible]
[illegible] 000 and 160,000					Resistances will be installed.	
[illegible]	Twice line voltage on complete insulators.	11 sets Electrolytic	4½ in. gap.	Yes	Daily, resistance used.	[illegible]
		Multigap and electrolytic	125% of normal voltage	Yes decidedly	3 times daily in summer, 2 times in winter, resistance used.	[illegible]
		Electrolytic and horn gaps, 2 sets Electro.; 9 sets horns.	150% of normal voltage	Electrolytic sometimes	Weekly, no resistance	[illegible]
		Electrolytic, 13 sets	115% of normal voltage	Sometimes	Daily, no resistance	[illegible]
		Electrolytic			Daily, no resistance	[illegible]
		4 Electrolytic	12%, set to barely discharge during switching		Daily—no resistance now but we are going to install them.	[illegible]
		9 Multigap and electrolytic.		Yes	3 times daily in summer, 2 times in winter, no resistance.	[illegible]
		None				
	None	23 Electrolytic	3.55 in.	Yes	Daily, no resistance	[illegible]
[illegible]	String 3 units 145,000	16 sets Electrolytic	[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]	[illegible]			[illegible]

25,000-50,000-VOLT GROUP

UTAH LIGHT & RAILWAY CO., (Ut. L. & R.) Utah.

O. A. Honnold, Electrical Engineer, Salt Lake City, Utah.

The data returned cover a portion of a very extensive system centering around Salt Lake City, Utah.

CANADIAN NIAGARA POWER CO., (C.N.P.) Niagara Falls, Canada, and Buffalo.

L. E. Imlay, Superintendent, Niagara Falls, N.Y.

The data returned cover a trunk line from Niagara Falls, Canada, to Buffalo. It represents four heavy capacity lines, parts of which have been in operation a number of years.

MT. WHITNEY POWER & ELECTRIC CO., (Mt. Wh'y. P. & E.) California.

Fred G. Hamilton, Superintendent, W.D., Visalia, Cal.

A transmission distributing company located in irrigating district of Central Southern California.

UNION TRACTION CO. (Un. T.) Indiana.

G. H. Kelsay, Anderson, Ind.

The data returned cover construction of an interurban electric railway system of wide extent.

TABLES

Tables I to V, inclusive, herewith, give statistical information as to the several companies and are self-explanatory. Where the information submitted has been too extended to incorporate in the table, it is given in the following notes.

NOTES REFERRED TO IN TABLES

NOTE 1. Angles are turned by shortening standard spans and taking only part of angles exceeding 10 deg. on any one pole. Below 10 deg. the following table is used:

Angle	Span
0 deg.	600 ft. tangent.
2	500
4	400
6	300
7	200
8½	100
10	50

On angles over 50 deg. the last tangent span is made 300 ft.—the first and last angle spans are 50 ft. with an angle of 5 deg., and subsequent spans are 50 ft. with 10 deg. angle each.

Vertical angles are similarly handled.

NOTE 2. Right angles and heavy angle corners are turned by specially guyed dead-end poles, Fig. 6, —angles under 10 deg. turned by standard poles guyed, and angles from 10 to 30 deg. are made on two or more poles. Vertical angles are not specially constructed except as to guying.

NOTE 3. Mex. L. & P. reports that the altitude is important. Gaps are set as follows:—Necaxa, altitude 2950 ft., voltage 85,000, gap 6 in.; El Oro, altitude 8000 ft., voltage 81,000, gap 6 in.; Pachuca, altitude 8000 ft., voltage 84,000, gap 7 in.

NOTE 4. Lumping together total interruptions and partial interruptions, and in the latter including even minor losses of load, such, for instance, as a direct-current breaker on a synchronous motor-generator set opening up, although the synchronous apparatus holds in, we have the following percentages:—

Lightning	.50 per cent	
Distributing cables	.25 "	
Miscellaneous	.25 "	—including buzzards on transmission line, operators' faults, and machinery breakdowns.

NOTE 5.

Floods and washouts on line	50 per cent	
Pole tops burning off or failure of insulators	.25 "	
Errors in operation	5 "	
Malicious interference	.20 "	

NOTE 6.

Lightning	.70 per cent approx.	
Wind, rain, sleet, etc.	.10 "	"
Interference	5 "	"
Errors	5 "	"
Miscellaneous	.10 "	"

NOTE 7. a. 1907—1912, possibly 10 or 12.
1912, possibly 10 or 12.
1913, possibly 5.

It is almost impossible to tell whether these insulators were punctured resulting in their breaking, or whether they cracked due to a spill-over and then punctured. With the new insulator or Hirt type very little damage can be done by spill-over.

b. From 1907—1912, about 150 insulators lost.
1912—about 75 insulators lost, and about 200 others changed on account of cracks.
1913, about 200 insulators changed on account of cracks and probably 50 insulators lost.

NOTE 8. The telephone system is protected by:—
a. A No. 8 steel ground wire carried on the same crossarm as the telephone wires, and on the side toward the transmission line.
b. Drain coils at terminals and at the two substations.
c. Vacuum arresters and spark gap at all telephone stations permanently connected to line. Aluminum cell arresters at terminals and at Hulls substation.
d. Insulating transformers at power house and substations.

NOTE 9. Telephone wires transposed according to "A", "B"-"C"-"B" system. "A" transposition between pairs; "B" and "C" transposition between wires of each pair.

NOTE 10. No standard distance for transposition. Our 28-mile two-circuit tower line has three complete cycles in each circuit. The majority of pole lines have a transposition every mile (one cycle every three miles). Where our high-tension lines parallel foreign telephone or telegraph lines, transpositions are made every 1/3 mile.

NOTE 11. Long fuses (30 inches long) with spark gap to ground. At all stations "bleeder" coils with middle point grounded are installed. Operator must stand on insulated platform to use telephone.

NOTE 12. Reactance coils are used in main low-tension buses in the power house between groups of generators.

NOTE 13. Between the low-tension bus and the transformers at the power house, and between certain sections of the bus at the power house and at the substation.

Short-circuit current on transmission line at full voltage in power house, right outside the power house, is about 5 to 6 times normal full load current at start.

Without these reactances the starting wave of the short-circuit current at the same point would be about 8 to 9 times full load current.

No objectionable features. These coils have been in service all year 1912 and 1913.

NOTE 14. The coils will be located between sections of 12,000-volt generator busbars and will limit the flow of current to the capacity of the bus section which it protects.

NOTE 15. Coils will have 6 per cent reactance, and will be placed close to terminals of the 12,000- and 15,000-kw. steam turbines.

NOTE 16. The factor of safety of new poles is entirely up to the judgment of the designing engineer, and depends greatly on the climate, kind of soil and economic conditions. Our towers were built to stand if all conductors were cut on one side, and no allowance was made for the tendency of the ground wires to support the tower.

Specifications for Towers.

Each crossarm will be sufficiently strong to withstand a horizontal strain in any direction applied at the end of the crossarm of 5000 pounds; and a vertical strain applied at the end of the crossarm of 1000 pounds.

Each ground wire support will be sufficiently strong to withstand a horizontal strain in the direction of the line of 8000 pounds and a vertical strain of 1000 pounds.

Each tower will be sufficiently strong to successfully resist the turning moment due to the application of a horizontal strain in the direction of the line of 5500 pounds applied at the point of support of either ground wire; also of a horizontal strain in any direction of 3000 pounds applied to the points of support of any three of the conducting wires. It will also be sufficiently strong to successfully resist an overturning due to a strain parallel with the line of 5500 pounds applied at the points of support of the two ground wires or a total of 11,000 pounds; also to a strain at right angles to the line of 5000 pounds applied at the points of support of the two ground wires or a total of 10,000 pounds; also to a strain of 9000 pounds in the direction of the line, which load will be considered as concentrated at the intersection of the middle crossarm and the center line of the tower, and simultaneously a horizontal strain of 500 pounds at the points of support of each of the six conducting wires and two ground wires or a total of 4000 pounds, which strain will be in a direction transverse to that of the line; also of a stress of 12,000 pounds applied horizontally at center of gravity of wires either at right angles or parallel to the line. Accompanying the above mentioned horizontal stresses will be a vertical downward strain of 500 pounds applied to each of the supports of the six conducting wires and two ground wires.

In addition to the above specified stresses each tower will be subjected to stresses due to its own weight and to a wind pressure in a horizontal direction of twenty pounds per square foot on the superficial area of the tower. The strength of each tower will be sufficient to resist the combined action of all of the above stresses without permanent distortion.

NOTE 17. Old insulators assembled test 120,000 volts for 1 min. New insulators, each disk tested with a low capacity transformer having steep wave front for 2 min. of continuous static discharge over insulator. Strain insulators same test.

NOTE 18. A special test tower was constructed and tested with following tests and all towers were built as duplicates of test tower:—

Test No. 1. A horizontal pull of 12,500 lb. in a direction parallel or at right angles to the lines will be applied at the intersection of the middle crossarm and the center line of the tower.

Test No. 2. A horizontal pull of 4,000 lb. in a direction parallel to the line and applied at the ends of any two crossarms (aggregate pull 8,000 lb).

Test No. 3. A horizontal pull of 6,000 lb. in a direction of the line applied at the end of any crossarm.

Test No. 4. A vertical load of 1,500 lb. applied at the end of any crossarm.

The tower must withstand the above force without permanent distortion in any member, and if such distortion should take place the contractor must replace such members with others until the tower successfully meets the requirements of the tests.

All of the standard towers covered by this contract must then be constructed strictly in accordance with the design and sizes of material contained in the successful test tower.

NOTE 19. On three of the present four 22,000-volt circuits from Niagara Falls to Buffalo on the Canadian side are in use electrose insulators which have been in service a considerable number of years. The fourth line which was installed in 1912 also uses electrose insulators but of a radically different design planned to be puncture-proof in severe impact tests. Test and forms of these insulators are described in the Trans. A. I. E. E., p. 2121, Vol. XXXI, meeting December 1912.

NOTE 20.	Winds, floods, fires, etc.	35 per cent
	Interference, blasting stumps, etc.	20 "
	Lightning	5 "
	Failure in equipment or insulators	15 "
	Miscellaneous and unknown	25 "

NOTE 21. The foundations of towers consist of 7-ft. legs with foot piece, the whole generally loaded with stone and well backfilled.

NOTE 22. Material of insulators porcelain with slate glaze. (Slate glaze shows up arc smoke marks better than brown glaze and attracts the attention of gunners less, but does not show up broken petticoats as well).

NOTE 23. The towers were built for two ground wires, but only one ground wire located on apex of tower was erected. This makes the horizontal spacing from ground wire to conductor 7½ ft. and the vertical spacing 7½ ft.

NOTE 24. All standard towers set on earth stubs, while the heavy towers are set in concrete.

TOPICAL TREATMENT

A large number of comments made by the various reporting companies on a number of topics of especial interest to engineers are here grouped together under their appropriate subjects as follows:

LONG SPANS (QUESTION A-19)

The following notes of interest were returned:

Miss. P. Longest span with standard tower and conductor 1425 ft.

The maximum span used on this line is 3200 feet, and occurs at the crossing of the Missouri River. This and other long spans are shown in plan and profile on the accompanying drawings (Figs. 30, 31 and 33.) The conductor cable in these spans consists of a ⅝-in. high-strength galvanized 19-strand steel core overlaid with 20 strands of No. 10 B. & S. gauge hard drawn copper wire. The cable is filled with a compound for the exclusion of air and moisture. Each circuit is carried on a single tower line, conductors in a horizontal plane, spaced 20 ft. apart, with two ground wires 10 ft. above at point of support. These river crossing towers were especially designed and vary in height from 60 to 230 ft. above foundations. See drawings.

Gt. Wn. P. One span 2300 ft. on special towers; one 2740 ft.

with No. 000 B. & S. "Minot" stranded wire; conductor balanced by counterweights to give uniform tension—Figs. 3 and 4.

Mex. L. & P. One 1400 ft. with a difference in elevation of 350 ft.; cable size and towers standard.

Pa. W. & P. Longest span with standard conductors and towers 1280 ft. Longest span 1800 ft. with No. 0000 B. & S., 7-strand hard drawn copper and towers 115 ft. high over all above foundations. Span sag 120 ft. (6.7 per cent). Distance between conductors, vertically 10 ft., horizontally 15 ft.—Ground wires above conductors—no trouble.

City S. L. Dpt. Longest span 780 ft. standard double-pole construction.

Wash. W. P. One 1500 ft., ¼-in. "Siemens-Martin" steel as conductor.

San. J. L. & P. Span across Kings River at Piedra, six 3/0 aluminum cables, carried about 1700 ft. across river and anchored on hillsides to cedar poles. Two sets of three wires each are attached to two poles, wires in a vertical plane six ft. apart and attached to poles with two Locke No. 273 strain insulators. Guys are placed for each wire and run to anchorage in rocks. About 200 ft. sag is obtained with wires clearing river about 150 ft. All wires swing in unison in a high wind and no trouble has been experienced.

Niag. L. & O. P. See drawing, Fig. 34.

C. N. P. See drawing, Fig. 8. The transmission line crosses the Niagara River at Buffalo where there is a span of 2192 ft., from a 150-ft. tower on the American side to a 202-ft. tower on the Canadian shore. The tops of these towers are at the same elevation. The line is then carried over the village of Fort Erie with a span of 1667 ft. to a 61-ft. tower on Bertie Hill. The top of this tower is 107 ft. below that of the high tower. The minimum clearance of the cables above the river is 130 ft. On the high towers the cables are arranged on 15-ft. triangles and on the Bertie Hill tower on 10-ft. triangles.

The twelve conductor-cables are made up of 19 strands of No. 10 B. & S. gage bi-metallic wire and are stressed up to 5400 lb. This tension is kept constant by counterweights on the Buffalo and Bertie Hill towers. The counterweights are supported by steel cables which run over sheaves at the top of the towers and are connected to each bi-metallic cable through two pairs of spool insulators. Drop cables pass down and through

the tower to the Buffalo terminal station and on the Bertie Hill tower to the busbars. The busbars and switches are so arranged that any circuit on the pole lines can be connected to any circuit on the long spans. At the high tower, the cables are connected to galvanized iron chains which rest on insulated saddles and extend about 13 ft. on each side of the tower. Jumper cables are carried over the saddles.

In addition, spans of 800 and 1435 ft. were reported by other companies and no cases of trouble.

Special Features of Construction (Question A-20)

The following notes relate to special features of interest in construction:

Ap. P. All suspension insulators are ballasted with 30-lb. cast iron weights. (See Part I of this volume of Transactions, page 133).

Port. R. L. & P. Experience has shown that it is cheaper and quicker to erect steel towers in position from the ground up.

Anchor Towers on Tangents (Question B-13-15).

The following reports were made on the use of anchor towers on tangents:

Miss. P. Approximately every mile.

Gt. Wn. P. Average every two miles—designed to stand with all wires cut.

Ap. P. Two per mile—designed to stand with all wires cut.

Sou. S. P. Every five miles, designed for 24,000 lb.

Pa. W. & P. At least every fifth tower—on average five to mile.

San J. L. & P. Poles guyed both ways every half mile, will stand with three conductors cut.

Niag. L. & O. P. Every mile on steel towers; every half mile on "A" frames; all to stand with all three conductors cut.

Sou. C. E. No, use line guys.

Ut. L. & R. Every 1½ to 3 miles, according to wind conditions; designed to stand 7000 lb. at center crossarm in addition to stress on regular line towers.

C. N. P. Only at two ends of line and two intermediate curves; designed to stand all conductors cut.

DETERIORATION (QUESTION A-25)

The following interesting notes on deterioration were received:

Gt. Wn. P. Slight rusting where towers were not properly galvanized. Wires corrode.

Yad. R. P. Line two years old—no deterioration noticed.

Pa. W. & P. No deterioration observed upon examination of buried portions of galvanized towers. One particular set of gusset plates near top of tower showing signs of rust during 1913; no rust or deterioration elsewhere. No signs of deterioration in conductors. Insulators both on transmission line and in stores showing deterioration, due possibly to temperature expansion effects. About 4 per cent of insulators examined show such deterioration, not due to electrical causes.

Wash. W. P. We have noted no deterioration in conductors. Some insulators placed in service in 1904-1906 indicate that they may have deteriorated, but as the manufacture of porcelain at that time was far less efficient than now, no results of long time tests on those would indicate what will obtain on the ones of later manufacture. Towers were placed in 1910, and no deterioration has been noticed.

Tor. P. Except for some deterioration of ground wire and hemp core of conductor, no deterioration noticed.

San J. L. & P. No deterioration noticed as yet—60,000-volt system in use only three years.

Niag. L. & O. P. Galvanized towers develop rust spots in about seven years. Insulators to some extent deteriorate by puncture of an occasional skirt. No noticeable deterioration of cable except by occasional burning by arcs.

Port. R. L. & P. The transmission line has been in service less than two years and we have, therefore, no observations of deterioration except in the matter of insulators, there having been a considerable number of failures in suspension insulators and insulators in a strain position since the line was put in service.

Sou. C. E. Insulator shells crack, presumably due to expansion of cement or steel pin.

Ch'a V. R. L. & P. Insulators give more trouble with age.

Ut. L. & R. Wood poles with carbonized butts last 10 years in this climate.

Pug. S. T. L. & P. None, if proper factors of safety were observed in original installations. Steel towers have to be painted every two years, if not galvanized. Cedar poles rot off at the ground in from 15 to 20 years.

City S. L. Dpt. Poles rot at ground line.

DEFLECTION OF SUSPENSION INSULATORS (QUESTION B 20-21)

As to how much angular deflection of conductor was assumed under wind conditions and how much was actually observed, the following data were reported:

Miss. P. 26 deg. 45 min., with ½ in. ice, assumed.

Gt. W'n. P. 45 deg. assumed.

Yad. R. P. 45 deg. assumed.

Ap. P. 30 deg. on swinging of strings; held down by 50-lb. weights.

Sou. S. P. 45 deg. assumed—45 deg. observed on swings.

Pa. W. & P. Approximately 60 deg. Probably never more than 30 deg. angular deflection from vertical due to wind observed under either steady wind conditions or swings. No good records on actual angular deflection. Conductors do not swing violently, and angular deflection is not the same at all points in a span for one conductor, but is the same for all conductors. See drawing, Fig. 54.

Wash. W. P. 50 deg. assumed, 36 deg. observed.

Ut. L. & R. 60 deg. from vertical assumed, this value observed in swings.

DESIGN FACTORS OF SAFETY (QUESTION B-22)

As to the factors of safety provided in conductors, towers, against overturning foundations, and overhead ground wires, the following data were reported:

Miss. P. Conductors 2, towers 3, foundations 2, ground wires 2.

Gt. Wn. P. Conductors 2, towers 2, foundations 3, ground wires 3.

Yad. R. P. Conductors 25,000 lb. per sq. in.

Mex. L. & P. Conductors 2 and 3, foundations 1.5.

Ap. P. Conductors 2, 3, towers 2, foundations 5, ground wires 10.

Sou. S. P. Conductors 2.5, towers 1.7, foundations 1.7.

Pa. W. & P. For conductors (alum.) up to elastic limit—towers tested for maximum designed strength at factory—foundations practically 4—ground wire just up to elastic limit.

Wash. W. P. For conductors elastic limit, for towers 1, for foundations 1, for ground wire 1. These factors are taken in view of the fact that the maximum load conditions assumed were very severe.

San. J. L. & P. For conductors 6, for poles 3.

Niag. L. & O. P. For conductors 1 (elastic limit), towers 2, foundations, 2.

Sou. C. E. For conductors 22,000 lb. per sq. in working stress.

City S. L. Dpt. Factor for conductors of 3 over elastic limit.

Overhead Ground Wires as Part of Structure (Question B-23)

In answer to the question as to whether overhead ground wires are relied upon as part of the line structure most of the companies replied *no*, but the following comments were received.

Yad. R. P. Yes.

Pa. W. & P. Ground wire gives some stiffness lengthwise of line, damping longitudinal vibrations of towers, but is not relied on as part of the mechanical supporting structure.

Ut. L. & R. No, but it undoubtedly acts as a guy wire.

Cutting Out of Load (Question C-1)

A loaded circuit is usually cut off by an oil switch, sometimes on high tension, sometimes on low tension. The following replies are noted:

Gt. Wn. P. Drop generator load and open generator oil switch on low-tension side. Do not switch on high-tension side.

Yad. R. P. (a) Reduce voltage 60 per cent and then open low-tension oil switch. (b) Open low-tension oil switch at full voltage. (c) Open high-tension oil switch at full voltage.

Mex. L. & P. Cut out sections of line one at a time loaded or unloaded. Experience shows that this method gives less trouble from surges on oil switches and switch bushings.

Opening Short Circuit. (Question C-2)

To open a short circuit that holds on, the following companies reduce the voltage of the generators:

Miss. P., Gt. Wn. P., Sou. C. E., C. N. P.

Note also the following comments:

Sou. S. P. The hydroelectric plants are tied in by non-automatic switches on the low-tension side while the steam plant has oil breakers with definite time limit relays on the low-tension side. The high-tension switches in the main tower line are of the Bowie air-break type and are non-automatic. As operated at present, when short circuit occurs on tower line, the steam

plant breakers clear the southern end of the system of trouble, leaving the steam station with all load in that territory. The hydroelectric plants then drop voltage to low value and test for location of trouble.

Sou. C. E. Separate main system into sections and cut out step-up transformers on high-tension side.

Automatic Overload Relays (Questions C 3-8)

Automatic overload relays are generally used, and in many parts of the various systems. The majority are definite time limit or inverse time limit.

The overload settings run from 100 per cent to 300 per cent overload, and the definite time limits from ½ to 10 sec.

A half-dozen companies use overload relays of progressively greater time element distributed from the load to the generator.

Miss. P. Use inverse time limit automatic overload breaker to cut apart groups of generators on the 11,000-volt generator busbars.

Niag. L. & O. P. and *Sou. C. E.* report success with this selective action; *Yad. R. P.*, *Mex. L. & P.*, and *Wash. W. P.* report partial success.

Pa. W. & P. Automatic overload circuit breakers are used in connection with 13,000-volt cable feeders, station auxiliary transformers at both power house and substation, and transmission lines, in the last case, however, not the high-tension circuit breakers, but the low-tension circuit breakers of those transformers connected with the line being opened.

In connection with 13,000-volt cable feeders, we use inverse-time relays; for the transformers and transmission line, definite-time relays.

(a) The lowest tripping current for the relays connected with our 13,000-volt cable feeders is 100 per cent overload, based on cable rating; with 700-1400 per cent overload these relays will trip in 1 sec. (inverse time).

(b) The relays for the substation transformers are reverse-power relays set to trip at 50 per cent overload in reverse direction, and connected with a three-sec. definite time element.

(c) The power house transformer relays trip at 140 per cent overload, 7 sec. definite time.

Time-element relays are normally used with progressive timing of the elements. This refers particularly to the relay system used for the 13,000-volt a-c. underground cable system in

Baltimore, of which a part belongs to the Pa. W. & P. Co. and a part to our customers' distributing systems. The larger part of the relays for this system are Type C Westinghouse overload inverse-time relays improved by F. E. Ricketts's compensating coil, which produces a relay curve with less steep characteristic and for heavy overloads can be brought to approach a definite time. Both tests and experience have shown that this type of relay can give good selective action for several relays in series.

Bellows type relays were previously used in this connection but were found to be not sufficiently reliable and were replaced by relays of the type referred to above.

Westinghouse Type C, improved, reverse-power relays with selective element are also used.

These reverse-power relays are used at the substation end of two transmission lines working in parallel. When a short circuit, which is not cleared in any other way, occurs on one line, it will trip the low-tension side of transformers at the substation connected with this line, while overload or time relays will trip the low-tension side of the corresponding transformers at the power house. If the other transmission line is not affected, the reverse-power relays for this line will remain open. In order to give another device (arc extinguishers) time to relieve lightning arcs, these relays for the transmission lines are furnished with definite time-limit relays (W. Type E); these have at present the following setting:

	Circ. No. 1	Circ. No. 2
Power house	3 sec.	2½ sec.
Substation	1½ "	1 "

The different time setting for the two circuits is chosen in order to prevent one line from opening at the substation, while the other opened at the power house, in case both lines should be in trouble. As soon as one circuit is cleared, an interlocking device prevents the other from opening by any relay action.

If after the clearing of one of the two paralleled transmission lines, the other still shows the trouble, the field will momentarily be taken off all the generators at the power house simultaneously, and restored again.

Should this action not clear the second line, the switches must be opened by hand. Our experience so far shows, however, that permanent line trouble (wires down, etc.) never has taken place on both circuits at the same time.

Pug. S. T. L. & P. Success generally but not always.

Aside from the *Pa. W. & P.*, the *Ut. L. & R.* and *Pug. S. T. L. & P.* are the only companies using reverse-energy relays; the former reported "always" act selectively—the latter does not state the result.

Note also *Cty S. L. Dpt.* Use Westinghouse Type C reverse-energy relays which act selectively when the power factor does not drop too low, as on a very heavy short circuit.

Dropping Synchronous Load (Question C-9)

The following report that they seldom or never succeed in carrying synchronous load through a heavy main-line short circuit:

Gt. Wn. P., Mex. L. & P., Sou. S. P., Tor. P., San J. L. & P., Port. R. L. & P., W. St's G. & E., C. N. P., Un. T., Cty. S. L. Dpt.

Other reports—

Ap. P. "Sometimes." Lightning arcs are frequently cleared by arc suppressors without losing synchronous load.

Pa. W. & P. Lightning arcs are frequently cleared without the least loss of load, by arc suppressors.

Wash. W. P. We have automatic switches on all lines feeding out of the different stations and when these act properly we very seldom lose any synchronous load.

Niag. L. & O. P. Save synchronous load by automatic arc extinguishers, when arcs only are involved.

Ut. L. & R. Yes, when short circuit is cleared in three seconds.

Pug. S. T. L. & P. Sometimes we can and sometimes we cannot. If the duration of short circuit is three or four seconds, synchronous apparatus always drops out.

Cutting Out One of Two Parallel Lines (Question C-10)

In answer to the question whether one of two lines parallel at both ends could be cut out without losing the load the following were received:

Miss. P. Two St. Louis lines parallel at both ends and have been separated in a number of cases automatically without losing the load.

Mex. L. & P. Four lines are operated in parallel and as a rule one line can be cut out without losing the load.

Ap. P. Sometimes.

Wash. W. P. Have such lines but cannot cut them out without losing load.

San J. L. & P. Lines are tied together at load end by tie-breaker set light; at supply end, lines are separated by operator.

Niag. L. & O. P. Have tried this but have abandoned the attempt.

Port. R. L. & P. Yes, but cannot be automatically separated.

Sou. C. E. All main lines, cannot separate.

C. N. P. Cannot separate such lines.

Un. T. Cannot separate such lines.

Locating Trouble (Question C-11)

Practically all plants sectionalize the line, test with generator voltage and patrol to locate line trouble.

Yad. R. P. Use also a Wheatstone bridge method.

Niag. L. & O. P. Use a special loop test described in the Trans. A. I. E. E., June 1907.

C. N. P. Uses a loop test.

Distribution of Power between Power Houses and Regulation of Voltage (Questions 20 and 21)

No points of especial interest appear in answer to questions on how power distribution between generators and voltage regulation are secured.

Effect of Heavy Short Circuit (Question C-23)

As to the effect of a heavy short circuit near one power station on a large system:

Pa. W. & P. When a short circuit occurs near one power house, the effect of this depends entirely on how long a time it lasts.

(1) If it is a lightning arc on the transmission line it will normally be cleared by arc suppressor.

(2) If it is cable trouble on the 13,000-volt distributing system, it will normally be cleared by opening automatically the proper feeder switches. If the trouble hangs on for more than four seconds the fields of the generators will be destroyed and restored automatically at all three power houses simultaneously.

Operation with One Side Grounded (Question C-29-31)

In answer to a question as to whether the lines were ever operated with one side grounded, even for a brief period, the following were received:

Pa. W. & P. For a few minutes, no effect; ground was cut off by the time the ground resistance was red hot.

Ut. L. & R. All one night on 28,000-volt circuit; no effect except unbalancing of system.

C. N. P. For about two hours with no effect except a slight unbalancing of current in conductors.

Ap. P. For two hours with no effect.

Wash. W. P. For several minutes causing whole system to be unbalanced.

Gt. Wn. P. For about ½ hour; one oil switch bushing and one string of insulators punctured.

Sou. S. P. "No; effect too severe."

Tor. P. On several occasions for five to fifteen minutes, on one occasion four hours. On the occasion when the system was operated for four hours the ends of the cable that were down were 1000 ft. apart, the ground was highly charged and the barbed wire on the right-of-way fence was also highly charged. A man attracted by the display due to this ground walked into the charged area, then tried to climb the barbed wire fence and was killed. A dog approached the barbed wire fence some distance away and after investigation started for remote regions. Claims were made for damages to cattle. These were paid, although it could not be found that any cattle were really injured.

In operating on a ground we have no means of knowing whether or not the wires are down, and as it is possible that there may be two grounds miles apart with an open circuit in the conductor between, we consider it a very risky thing to continue such operation and would only do so as a last resort.

San J. L. & P. For two and a half hours on 60,000 volts; for one and one-third hours on 30,000 volts. The effect was unbalanced voltage on the particular feeder having a ground; unbalanced load on nearest generating plant, private telephone line out of commission, troubles reported from Sunset and other telephone systems.

Niag. L. & O. P. On one occasion when neutral was not grounded, for two hours; effect "violent."

Pug. S. T. L. & P. For 10 minutes,—severe strains, discharging lightning arresters—telephone wires hot.

Relays in H-T. Ground Connection (Question C-32)

No plant of those reporting except *Pa. W. & P.* (see below) seems to have any protective relay in the ground connection

from the high-tension neutral, except for the fuse of the Nicholson arc suppressor.

Voltage Regulators (Question C-41)

The use of Tirrill regulators to control the voltage of generators is almost universal and there appears to be no exception to the satisfaction they give.

Failure of Oil Switches (Question C-43-44)

As to whether oil switches have ever failed to open a circuit, most companies report no trouble, but the following are noteworthy:

Mex. L. & P. Very rarely.

Sou. S. P. No, but signs of distress are often shown. Most of the trouble from oil switches occurs in the breakdown of bushings from lightning or surges.

Tor. P. H-3 oil switches have failed repeatedly when more than four 10,000-kw. generators can feed through them to a short circuit.

Niag. L. & O. P. Yes, from repeated operation on short circuit without overhauling.

Ut. L. & R. 4000-volt, three-phase oil switch on overload.

Sou. C. E. On short circuits; the system has outgrown the size of the switch.

Pug. S. T. L. & P. Oil switches which are type H-3 and K-10 have always opened short circuits successfully but sometimes the switches are nearly wrecked.

Working with Adjacent Line Alive (Question C-45)

Practically all companies except *Cty. S. L. Dpt.* work on one of two lines on the same poles or towers when the other line is alive.

Which Insulator of Suspension String Fails First (Question C-48).

As to which insulator unit in a string of units is most likely to be injured, note the following:

Gt. Wn. P. Insulator next to line, but in general it is hard to tell.

Pa. W. P. Flash-overs damage first and last units preferably.

Wash. W. P. Nearly always the first and last of the string.

Port. R. & L. No difference.

Ut. L. & R. End disks.

Relative Reliability of Suspension and Strain Insulator Strings (Question C-49)

There is a difference in experience as to whether strain insulators are more likely to fail than vertical strings. *Port. R. L. & P.*, *Ut. L. & R.*, *Pa. W. & P.*, *Wash. W. P.*, and *Yad. R. P.* say "no." *Gt. Wn. P.* and *Sou. C. E.* say "yes."

Reactance to Balance Charging Current (Question C-51)

Sou. S. P. has the following to report about the use of reactance coils to control the power factor of the line.

Shunt inductance coils are used at one end of tower line. These have loading value of 2000 kv-a. and are arranged for being cut in by steps. They have been found valuable in the tieing together of the two systems of plants, enabling the steam plant to get in with the hydro plants with little voltage disturbance, which there would be if steam plant had to raise voltage to value high enough to equal voltage at end of unloaded line; this is about 14 per cent high.

Mechanical Oscillations (Question C-52)

With regard to trouble with mechanical oscillations in the line note the following:

Port. R. L. & P. Trouble occurs at far end of 30-mile, 33,000-volt, 33-cycle line when fed from one generating station only and given a heavy load. Line pulsates and finally kicks out at generating plant.

Ut. L. & R. No trouble except wind swinging suspension insulators enough to break them.

Wash. W. P. No, except that ice falling off the end ones of a group of three spans allows the ice in the middle span to carry this span down too close to conductor in the position below.

Mex. L. & P. Two during earthquakes.

In addition to the above, note the following replies received to a special inquiry about mechanical oscillations:

Gentlemen: New York, April 13th, 1914.

On January 8th, the Engineering Data Committee, at the suggestion of Mr. L. E. Eustis, Superintendent of the Stone and Webster Engineering Corporation, sent a letter to a number of high-tension power companies asking for any available experience with mechanical vibrations or oscillations of line conductors. You may be interested in the enclosed summary of the replies received. Yours very truly,

Percy H. Thomas, Chairman,
Engineering Data Committee.

Replies to Letter of January 8th Relating to Experience with Mechanical Vibrations or "Oscillations" of Line Conductors

C. N. P.

"This phenomenon was experienced by us in the aluminum cables which originally spanned the Niagara River between Fort Erie and Buffalo. The vibrations were most pronounced when there was little if any perceptible movement of the air. The cause was doubtless due to the physical constants of the span cables and possibly their supports being such that they would readily respond to slight movements of the air. Our evidence of this is that when the tension was decreased, allowing the cables to sag a few feet below normal, no vibration occurred.

At first we had some trouble with the cable strands breaking at the end supports due to crystallization of the metal. This was overcome by inserting about ten feet of iron chain in each span where the ends are attached to the supports. The chains were then shunted with jumpers to provide the necessary carrying capacity.

After a few years' experience with aluminum cables at the long spans, it was decided to replace them with copper-clad steel cable having much greater tensile strength. These cables are somewhat heavier than the aluminum, but are smaller in cross-section. They are pulled up to the same elevation as the aluminum cables, but, due to the different physical constants, no vibrations have been observed under any weather conditions."

Niag. L. and O. P.

"Please note that we have frequently noticed such oscillations but never have found any harm to result from them. Such oscillations are particularly noticeable on long spans, although they occur to some extent on all spans."

Oregon E. R.

"Wish to say that we have had no serious trouble from this source, and have had no data or experience along this line that would be of interest."

Tor. P.

"We have no spans comparable to the Mississippi River crossing at Keokuk, Iowa. We have, however, given consideration to crossing the Niagara River where we have had to figure on 4000- and 6000-foot spans. It was necessary for us

to consider mechanical oscillations of the cables due to changes in temperature, ice loading, wind, and the vibrations that would be started by short circuits, and we concluded that proper spacing, counter-weighting and keeping the cables at suitable temperature by means of local currents from insulated transformers or generators, would afford us ample protection.

We have no spans over 1000 feet on our existing transmission lines and have had no troubles that we can assume are directly due to mechanical oscillations. We have had line interruptions during sleet storms which could probably be accounted for in no other way."

Pa. W. & P.

"The possibility of such phenomena was anticipated at the time our transmission line was designed and a special endeavor was made to so design the line as to prevent such oscillations. We believe that the many anchor towers used and the attention given to the conductor sags is responsible for our freedom from such trouble.

As stated in the previous answers, we did experience some troubles owing to the ground wire being stretched too tightly, so that it hummed and caused considerable vibration of the towers. It was found necessary to cut in additional slack into the ground wire. The ground wire had originally been strung very tightly in order to avoid interference between ground wires and conductors, due to the possibility of sleet collecting on the ground wire while being absent on the conductors. Also a tight ground wire was considered advisable in order that its period of vibration longitudinally might be quite different from that of the conductor."

"We have no evidence of mechanical oscillation on our 1800-ft. span river crossings."

From Mr. Magnus Swenson, President,

Southern Wisconsin Power Company, Madison, Wis. (dated 1/21/14)

"In answer to yours of the 8th will say we have experienced no trouble from mechanical oscillation on our line, nor has the Peninsular Power Company in the northern part of this state."

G. Wn. P.

"Will state that we have no record of any one having observed this phenomenon on our lines."

Pac. G. & E. (dated 1/20/14)

"This company maintains a large number of long spans on transmission lines, these varying from 200 to over 4000 ft. in length. On spans up to 1500 or 2000 ft. the conductor material is not of great importance, our experience being that there is very little choice between copper, aluminum, copper-clad steel and other materials.

On spans of more than 1500 ft. we have found it desirable for mechanical reasons, to use either copper clad, or steel conductors.

The longest span we have is that known as the "Carquinez Strait crossing," where the distance between supports is 4427 ft. The conductors on this crossing are of 7/8-in. plow steel, having ultimate tensile strength of 200,000 lb. per unit cross section. These spans have been in successful operation at 60,000 volts for 13 years. There is a small amount of vibration in the conductor at the point of support during days when there is no wind blowing, but during times when the wind is blowing the hardest there is little if any vibration whatever at this point.

A year ago one of the conductors of this span was taken down and a section near the supporting saddle was tested to determine whether or not there had been any appreciable deterioration of the metal either from crystallization or from electrical causes. A careful analysis and test showed that the cable was in apparently as good condition as it was the day it was erected.

On another line we have installed a large number of spans of 6/0 stranded aluminum, ranging from 1200 to 1800 ft. in length. No trouble has been experienced on spans of this length from the causes mentioned; in fact, this particular line is considered one of the most reliable that we have.

In a few instances trouble has been experienced from the vibration of the conductor, which has resulted in the latter breaking at the point of support. These instances, however, are very rare and we have attributed the trouble to the fact that the length of span and tension in same were just right for the wind to cause excessive vibration. In every instance where this trouble has occurred, the insulator has been the ordinary pin type. The trouble has been corrected by setting another pole, and thus introducing another point of support in the vibrating span."

From Mr. Chas. I. Burkholder, General Manager,
Southern Power Co., Charlotte, N. C. (dated 1/20/14)

"I have to advise you that on our lines having suspension insulators we have not had any trouble due to mechanical oscillations of line conductors, except in the case of unequal distribution of load due to sleet unloading from the lines. This has never occurred when the sleet was forming but has occurred when the sleet was falling off of the wire, in cases where it happened that the sleet fell off of one wire, we will say, in a given span, and remained on another wire, and where the opposite occurred in an adjacent span. This would cause an accumulation of sag in the unloaded span, and in some cases the accumulation of this sag has been enough to cause an actual contact of wires which were strung with a 10-foot vertical spacing. To obviate this, we lengthened our middle crossarm 3½ feet at each end."

Wash. W. P.

"I beg to state that we have never noticed any mechanical oscillations of our line conductors.

At one time we had some trouble which we were unable to account for, and thought that possibly it might be due to such mechanical oscillation. To satisfy ourselves on this point we short-circuited one of our 60,000-volt lines, about four miles from our Little Falls power house, without noticing any oscillation whatever in the conductors. This short-circuit was thrown on the line when it was connected with a 5000-kilowatt generator at the station, and as far as I remember now the automatic switch was set for ten seconds definite time limit."

Port. R. L. & P.

"We wish to state that we have not experienced any trouble. We have observed, however, the presence of waves along the conductors in an 1800-foot river crossing span. These waves appeared to travel along the conductors even on a quiet day. They were apparent only by listening to the insulators at the supports and manifested themselves in very much a similar manner to blows struck against the conductors with a wooden mallet. As the crossing span was removed within a year after its installation, and has not been replaced, we have no occasion to report actual trouble resulting from the waves. The crossing span supports are each located a short distance from railroad tracks and the waves which we observed appeared to have been started by passing trains."

From Mr. A. J. A. Kean, Chief Operating Engineer,
The Michoacan Power Co., Guanajuato, Mexico. (dated 2/10/14)

"In this connection we wish to advise you that we had this trouble on one of our transmission lines some two years ago and were able to eliminate the difficulty by using special hangers made in the form of a bow. If Mr. Eustis would care to send to us details regarding his trouble we may be able to supply him some information which will be of assistance to him."

From Mr. W. B. Stone, Chief Electrical Engineer,
Jhelum Power Installation' Baramulla-Kashmir, India.

"I beg to inform you that formerly when we had long river spans we experienced trouble which I attribute to this cause. The line wires became crystallized through fatigue close to the clamps on the insulators, and when the first fall of snow came they invariably carried away at this point. We have now removed all long spans."

From Mr. C. A. Sylvester, General Manager,
The Rio de Janeiro Tramway, Light and Power Co., Limited, Rio de Janeiro, Brazil.

"We have had no trouble which could be traced to mechanical oscillation of our transmission line conductors.

Our 88,000-volt transmission consists of 3/0 conductors erected on Riter-Conley type of steel towers, six conductors per tower. We have several spans exceeding 500 meters, the greatest span being 590 meters. Observation of the oscillations indicate a considerable side swing during heavy winds, but the wires apparently always maintain their spacing of eight feet. This is probably due to the fact that they are of the same weight per foot, same diameter, and are erected with the same tension. There is of course no unequal loading due to sleet.

It has been suggested that the vibration and oscillation of the wires may tend to break the conductors at the insulators. We have up to the present time observed no effect of that kind.

The lines have been erected since 1907."

Location of Lightning Arresters (Question C-2)

Lightning arrresters are freely located either inside or outside, and universally close to the outlet of a station.

Duration of Discharge on Electrolytic Arresters (Question D-10)

There is no report of over 1 minute of actual continuous discharge on an electrolytic arrester. At least two companies cut them out if they begin to discharge steadily.

Effectiveness of Overhead Ground Wire

With regard to the opinion of companies on the effectiveness of overhead ground wires as a protection against lightning, note the following:

Mex. L. & P. We have had overhead ground wires on our high-tension transmission lines for the past six years. In practical experience we have found that this has given us an excellent protection. The number of cases of trouble due to lightning has been enormously reduced since the installation of these ground wires. We can definitely state that we consider their installation as effective and desirable.

Ap. P. There is evidence in favor of the effectiveness of overhead ground wires but it is not conclusive.

Pa. W. & P. We have no reason to believe that the overhead ground wires have been of any benefit against lightning troubles.

Ch'a V. R. L. & P. We have wood pole lines 26 miles long without ground wire; there is a 12-mile extension with ground wire, same insulators and crossarms used; never had an interruption from lightning on 12-mile line; have 7 or 8 per season on 26-mile line and have many bad insulators that do not shut down line.

Ut. L. & R. Overhead ground wires on tower lines undoubtedly reduce static disturbances, as interruptions are much less frequent than before.

Special Protective Devices (Questions E-1-4)

In certain systems, devices operating through circuit breakers or fuses have been installed for the purpose of automatically freeing circuits from arcs, either between line wires or to ground. The principle of operation includes the momentary short-circuiting of the arc by automatic apparatus at some predetermined place, which opens the circuit as soon as the original arc is suppressed. The following reports have been received bearing on such apparatus.

Pa. W. P. We are using the arc suppressor invented and designed by L.C. Nicholson of Buffalo, N. Y. This device consists in a general way of electromagnetic relay switches connected in

series with the main transmission line. The overload caused by a flash-over produced by lightning closes these electromagnetic switches rapidly, and in this way short-circuits the wires between which the flash-over is taking place, with a fuse wire calibrated to blow in about 5-10 cycles. This device worked very successfully in 1912 and 1913. It is especially satisfactory when a ground or a short circuit takes place only between two of the transmission wires. In such cases, it saves all of the synchronous load. If a three-phase short-circuit takes place, the effect on the synchronous machinery is more serious. About 50 per cent of the load can, however, be saved, especially if the synchronous converters, of which the main load consists, are separately excited, so as to prevent reversal of polarity.

With the Nicholson arc extinguisher are also connected certain electrostatic relays, intended to work in such a way that when one wire becomes grounded, a switch will be closed, and by this means, a fuse wire, which is timed to blow in about 1/2 second, will be connected between the wire which is grounded, and the ground. This device worked successfully several times. The electrostatic relays which initiate this action seem, however, somewhat less reliable than the magnetic relays, which get into action on short circuits on the line. The electrostatic relays are at present cut out of service, due to the fact that the principle they are based on will make them operate unnecessarily and thus produce undesirable complications whenever the voltage on the line for a moment is lowered artificially by operation of field-destroying device.

In case the arc extinguisher as outlined above does not work, or does not extinguish the arcs, the field is automatically destroyed on all generators in all three power houses connected together, and after 1½ sec. the field is restored again automatically, and, normally a large part of the synchronous load will, in this way, be pulled into step again.

The relays, which in the main power house (Holtwood) actuate the field-destroying and restoring device are either one of the generator relays (in case of short circuit on the line) or the relay in the grounded neutral of one of the transformers connected with the transmission line; these relays act instantaneously themselves, but their action is delayed 4 sec. (by means of a definite time limit relay) in order to give other protective devices their chance. The main difficulty we have experienced with this device is to prevent the generators in the power house (water-

wheel-driven) when some of their prime movers were on "hand control" (*i.e.* had a steady gate opening), from speeding up the moment the field was taken off and thus getting decidedly out of synchronism. When originally installed, the time the field was left open (*i.e.* short-circuited with the standard discharge resistance) was 5 sec.; this time element has this year been cut down to 1½ sec. with the results much better in the above respect than formerly, and yet the time is apparently long enough to extinguish lightning arcs on the transmission line. The 1913 record until October 1st, shows that lightning has hit our lines 32 times resulting in three total interruptions, while the trouble was cleared successfully, with little or no loss of load, 18 times by arc extinguisher, 9 times by field-destroying device, and two times by relays opening one of two parallel circuits.

Tor. P. The circuit-breaker type of arc suppressor was tried but was not a success. The Nicholson electromagnetic type is being installed.

Niag. L. & O. P. Uses both Nicholson automatic grounding and Nicholson automatic short-circuiting devices.

Lowering Voltage to Clear Short Circuit (Question E-11)

In reply to question as to whether the voltage of generator is lowered in case of trouble the following were received:

Miss. P. Yes, by hand and automatically.

Gt. Wn. P. Yes, by hand.

Yad. R. P. Yes, by hand.

Sou. S. P. Yes, by hand, expect to install device to automatically lower voltage at time of short circuit or ground on line.

Pa. W. P. See notes under Special Protective Devices (Question E, 1-4 above),

Wash. W. P. No, only when line is on a single generator as a separate system.

Tor. P. Automatically.

San. J. L. & P. No.

Niag. L. & O. P. No.

Port. R. L. & P. On special occasions by hand.

Sou. C. E. Yes, by hand.

Cha. V. R. L. & P. No.

C. N. P. Excitation is from induction-motor-driven d-c. generators. The motors are supplied from busbars fed by the alternators which they excite. In case of a short circuit, exciter sets automatically slow down and reduce field excitation.

Pug. S. T. L. & P. Yes, have auxiliary relay on Tirrill regulator that prevents increase of field strength during short circuit.

Mt. Wh'y P. No.

Un. T. No.

Usability of Telephone Lines (Section F)

The conclusions to be drawn from the replies to the questions on telephone lines may be summarized.

In general no company can entirely rely on its telephone line when the power line is grounded and many cannot use their telephones while electrolytic lightning arresters are being charged. The effect of the grounding of the high-tension line is to make it noisy and to cause discharges over arresters and sometimes to cause telephone fuses to blow.

The following comments are noteworthy:

Gt. Wn. P. Most severe trouble is from a ground on the 100,000-volt line. This in general will cause a break over the insulation of the telephone line which is carried on 6600-volt porcelain insulators. To quiet the line, 2-kw. 2200/220-volt transformers used as drainage coils with the secondaries open were installed; these were successful.

Yad. R. P. The telephone line is said to be usable at all times and grounding of the transmission line to have no effect. This telephone line is from 500 ft. to one mile away from power line.

Sou. S. P. Telephone line not always usable. Most of trouble is due to mechanical faults occurring in telephone lines. Induction is also noticed. Arcing on horns of out-of-door switches is quite noticeable on telephone lines. Ground on transmission line makes telephone very noisy.

Pa. W. & P. Users of telephones protected by lightning arresters and fuses on line side of instruments. Insulating transformers used at Baltimore end of telephone line.

Telephone usable practically at all times during operation.

Telephone not usable only at time of ground on transmission line or during charging of electrolytic arresters.

Troubles on transmission line blow fuses or burn arresters on telephone line occasionally. Sometimes burn out telephones.

There has not been much trouble and talking is remarkably good on telephone lines—equally as good as Bell long-distance lines.

Niag. L. & O. P. Heavy induction by grounds on power lines sometimes blows fuses on telephone lines at stations. Telephone is practically always usable due to bleeding coils.

Cty. S. L. Dpt. Induced currents have caused telephone wires spaced 12 in. apart to wrap together. Line disturbances sometimes blow telephone fuses (¼ ampere). We do not attempt to use telephones while a disturbance is on line.

NOTE: The following description of the protective apparatus used by the Georgia Railway and Power Company to shield its telephone line from disturbances on the high-tension transmission line, together with an account of tests made thereon, has been furnished by Mr. E. P. Peck, Ass't. Electrical Engineer.

The telephone line of the Georgia Railway & Power Company from Atlanta to Tallulah Falls, a distance of 87 miles, has No. 4 bi-metallic conductors, insulated with single disk suspension insulators. These insulators have a dry flash-over test of 70,000 volts but it is the purpose of the company to connect two of them in series on the telephone line at the earliest possible date. The telephone line is strung on the main 110,000-volt tower line, about 10½ ft. from the lower power conductor.

The telephone line operates at a voltage to ground of approximately 5300 volts, when no drainage coils are connected. The voltage from line to line is very low, except in cases of insulation troubles on the main power line or on the telephone line.

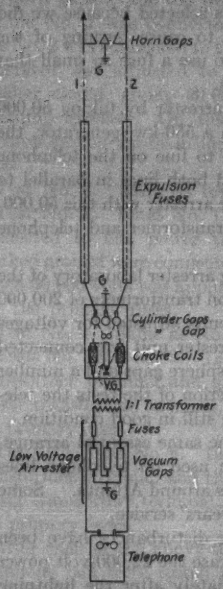
Trouble was experienced, due to the high voltage on the telephone line, and to remedy this, drainage coils have been connected at the Boulevard substation in Atlanta and at Gainesville substation. A drainage coil will be connected at the power house also, in a short time. A standard 15-kw., 2200-volt power transformer is used as a drainage coil. The 2200-volt leads of the transformer are connected to the line wires and the middle tap of the primary is connected to ground, the secondaries being left open.

With the drainage coils connected in Gainesville and in Atlanta, the voltage from the telephone line to ground is approximately forty-five volts, the drainage coils carrying a current of approximately 3.75 amperes, continuously, in the ground leg.

The telephones in all of the stations are connected to the telephone line through telephone transformers, insulated for 25,000 volts from primary to secondary.

A number of telephone transformers and telephones have

been damaged on this line, the damage resulting from lightning along the line or from leakage either on the main power system or on the telephone line. To stop the telephone and telephone transformer trouble, a lightning arrester has been developed which gives promise of excellent results. The apparatus (diagram of connections shown herewith) consists of proper relief gaps which are protected by expulsion fuses. The most important part of this arrester unit is a vacuum gap adjusted to break down at approximately 350 volts and connected from line to line. Adjustable cylinder gaps are connected from each line to ground and other cylinder gaps are connected in parallel with the vacuum gap. Choke coils, wound on porcelain cores and with turns very heavily insulated, are connected between the gaps and the telephone.



The action of the arrester in case of high voltage on the telephone line is as follows: A high voltage impulse being impressed on the lines equally, will raise the voltage of the telephone line and telephone transformer to a value sufficient to break down the air gap to ground and will not impress any high voltage across the terminals of the telephone transformer unless the ground gaps are set unequally, in which case the gap with the smallest setting will drain the wire connected to it directly and will drain the wire with the larger gap setting through the vacuum tube arrester.

If the voltage is impressed unequally on the telephone lines, the vacuum gap will spark across, holding the voltage across the terminals of the telephone transformer and the telephone to a safe, low value.

The choke coils are used to retard steep wave front impulses until the arrester gaps will have time to discharge.

It has been found that a continuous discharge through the vacuum gap will melt the solder and compound used to seal the case of the vacuum tube, allowing the vacuum to be de-

stroyed. The cylinder gap connected in parallel with the vacuum gap is for the purpose of holding the line-to-line voltage as low as possible in case the vacuum gap is destroyed. The lowest advisable setting on these cylinders will give an arcing voltage in the air of approximately 700 volts and the cylinder gap will never come into play unless the vacuum gap has been destroyed.

The expulsion fuses used are of five-ampere capacity and will not blow unless there is a very severe disturbance on the telephone line. The five-ampere fuse was selected because we did not wish to use a fuse large enough to cause burning of the vacuum gap or the cylinder gaps or to use a fuse so small that it would blow on slight disturbances.

A test was made on this lightning arrester by taking 50,000 volts from a power line supplied from a 550-kw. generator, the power line being connected from line to line on the telephone arrester, from each line to ground and both lines in parallel to ground. Eight tests were made on one arrester with this 50,000-volt power supply, with a telephone transformer and telephone connected during the tests.

Tests were also made in the lightning arrester laboratory of the General Electric Company on oscillation transformers of 200,000 and 500,000 cycles with oscillating circuits adjusted for voltages from 50,000 to 150,000 volts. An arrester unit was connected in parallel and in series with the main sphere gaps and a number of shots were made. After the completion of the tests the telephone transformer and telephone were still in good condition.

A number of small arresters with the same essential arrangement of the arrester parts have been used on telephone lines paralleling 11,000- and 22,000-volt lines around Atlanta. Some of these arresters have seen about two years' service.

A large number of severe lightning disturbances have been handled by these arresters and in one case the 22,000-volt power line fell on the telephone line immediately after the lightning stroke. The main wires to the arrester and the ground wires on the arresters at both ends of the lines were burned off and in this case as well as in all other cases no damage has been done to the telephone transformer or to the telephone. In the same territory a very large number of telephone transformers and telephones have been destroyed by lightning although they were protected by the best arrester system which we had been able to obtain from the manufacturers.

TEST OF TELEPHONE LIGHTNING ARRESTER TO BE USED ON TELEPHONE LINES ADJACENT TO 110,000-VOLT POWER LINES

One 555-kw., 440-volt, 60-cycle alternator was connected to a 625-kw., 440 to 50,000-volt transformer and the high side of the transformer used on the arrester tests. On these tests the circuit breaker of the transformer bank was set at 1600 amperes, the normal load on one generator being 625 amperes.

Test No. 1. Referring to the diagram on a preceding page, the horn gaps at the top were not used.

Line No. 1 was connected to one transformer terminal and line No. 2 was connected to the other transformer terminal. The generator was adjusted to give 50,000 volts and the circuit breaker closed, giving 50,000 volts directly on the telephone lightning arrester. On this test the cylinder gaps and the vacuum gap on the main line arced across, blowing the main line fuses.

Test No. 2. Same as test No. 1.

Test No. 3. Lines No. 1 and No. 2 were tied together and connected to one power transformer terminal and the leads marked ground were connected to the other transformer terminal. When 50,000 volts was applied the spark gaps arced across, blowing the primary fuses.

Test No. 4. Same as No. 3.

Tests No. 5 and No. 6. Line No. 2 was connected to one power transformer terminal, and ground gap connected to the other power transformer terminal. 50,000 volts was applied, blowing the primary fuses.

Tests No. 7 and No. 8. Line No. 1 was connected to one power transformer terminal, and the ground gap connected to the other power transformer terminal. 50,000 volts was applied, blowing the primary fuses.

After each of the above tests the 1 to 1 transformer and the telephone bell were tested and found OK. The vacuum gap connected on the high side of the 1 to 1 transformer broke down at 360 volts before the high-voltage tests were made, and broke down at 370 volts after tests were made.

It is of interest to note that the arrester on the low side of the telephone transformer never had its fuses blown, showing that all high-voltage strains were relieved before they reached the telephone transformer.

This test corresponds very closely to the condition which will obtain when one of the 110,000-volt power lines crosses with

either or both of the telephone lines. In this case the voltage will be 63,500 volts, while the voltage on the tests was 50,000. However, in service, 63,500 volts can never reach the telephone lightning arrester because the insulators on the telephone line will arc across at much lower voltage than this.

Preservatives for Wood Construction (Questions G-1-2)

The following information is received as to preservative treatment of wood poles:

The following companies treat wooden pole butts—either by brushing or open tank treatment using carbolineum, hot gas drippings, creosote oil, or hot tar.

Miss. P. (cost 10 cents per pole), for brush treatment only.

Gt. Wn. P.

Ap. P.

Sou. S. P. Open tank process.

Wash. W. P. Carbolineum oil on cedar poles; two feet above and below ground line. Tamarack poles treated by charring 6 ft. below ground line and pouring hot carbolineum oil over charred surface. Cost 25 cents per pole.

San J. L. & P. Open tank process; average penetration 5/8 in. for 8 ft. on butt; cost approx. $1.50 per 50-ft. pole.

Niag. L. & O. P.

Ch'a V. R. L. & P. Open tank; cost 40 cents to $1.50.

Ut. L. & R. Cost one quart carbolineum and 10 cents labor per pole.

Mt. Wh. P. & E. Paint poles; cost 50 cents per pole.

Un. T.

Treating Crossarms (Questions G-3-4)

The following companies treat crossarms and pins as specified:

Yad. R. P. Crossarms and pins, open tank, four hours in oil 100 deg. cent. 4 hours in cold oil.

Ap. P. Crossarms same as butts.

Sou. S. P. Crossarms and pins same as butts.

San J. L. & P. Crossarms given two coats of good paint.

Niag. L. & O. P. Crossarms creosoted in open tanks or treated with avenarius carbolineum.

Port.R. L. & P. Crossarms dipped in preservative.

Ch'a V. R. L. & P. Crossarms brush treated.

Ut. L. & R. Crossarms, paint and oil; pins paraffin.

C. N. P. Pins on new line impregnated with bakelite.

Mt. Wh. P. & E. Pins boiled in linseed oil.

Un. T. Crossarms and pins—open tank creosote treatment.

Cty. S. L. Dpt. Boiled in carbolineum.

Gain in Life by Treatment (Question G-5)

With regard to the gain in life from treatment note the following:

Gt. Wn. P. No deterioration as yet.

Sou. S. P. 5 to 10 years, based on older Colorado-Nevada Power Co. System.

San. J. L. & P. Creosoted butts have lasted 6 years on pine poles, that would otherwise decay in 16 months. We have only been treating pole butts for 6 years, but our experience shows the protection afforded is well worth the cost. Our principal pole timber is Washington red cedar.

By creosoting butts and properly painting crossarms, the wooden pole line should have a life of at least 25 years. We have a square sawed redwood line, carrying six No. 3 copper conductors at 30,000 volts (and a portion of the time 60,000 volts), 35 miles long. This was built 8 years ago and pole butts were *not* treated. Recent patrol and inspection showed 70 per cent of poles perfectly sound above and below ground.

Niag. L. & O. P. Crossarms in good condition; poles show various amounts of decay at ground line.

Port. R. L. & P. Poles last 12 to 15 years without treatment and under favorable conditions treatment may add two or three years to life of pole.

Ch'a V. R. L. & P. Life of poles has been increased.

Ut. L. & R. 10 years in dry climate.

Cty S. L. Dpt. Crossarms 12 years old show no depreciation.

Outdoor Oil Apparatus (Question H-4)

As to the general satisfaction with outdoor transformers, oil switches and substations, note the following:

Miss. P. Satisfactory.

Yad. R. P. Satisfactory, are using them exclusively in high-tension work.

Ap. P. Yes.

Sou. S. P. Outdoor stations on transmission line serve as switching stations as well as transforming stations. Two switches are cut into each of these two lines passing through the station and a paralleling set of disconnecting switches for lines. Steel is used throughout for the supporting structures. Transformers

are all provided with trucks and each station has a transfer track and truck for moving transformers into a building which contains a pit and lifting rig and also serves as a storeroom for supplies and repairs. We have every reason to be pleased with the outdoor type station of this character.

Wash. W. P. Cheaper and satisfactory.

San J. L. & P. We place station transformers on separate foundations, about 35 ft. apart. Poles are placed directly back of each transformer, to which are attached, by strain insulators, the high-tension and low-tension leads to the switch house. The switching house protects both high-tension and low-tension switches and metering equipment. This house is usually a frame structure covered with galvanized iron. Current transformers are installed indoors and potential transformers on poles outside. These stations have proved very satisfactory.

Niag. L. & O. P. Westinghouse outdoor type GA, oil circuit breaker satisfactory.

Ch'a V. R. L. & P. All standard and entirely satisfactory.

Mt. Wh'y P. & E. Yes.

Cty. S. L. Dpt. Outdoor bushings all right on electrolytic lightning arresters.

Use of Breathers (Question H-5)

Most companies report that they do not use breathers in outdoor transformers but the following may be noted:

Yad. R. P. Use chloride of lime breathers but do not consider them necessary.

Mt. Wh'y P. & E. Yes, no trouble so far—use inverted elbow and fine mesh screen.

Penetration of Water in Outdoor Transformers (Question H-6)

Most companies report that no water penetrated weatherproof tanks, but note—

Yad. R. P. Not when in operation and temperature high.

San J. L. & P. In some of smaller sizes of transformers (100 kw.) moisture has penetrated the tanks. However, other installations of exactly similar make and capacity gave no trouble.

Outdoor Type High-Tension Bushings in Wet Weather (Question H-7)

Most companies report that outdoor type bushings operate satisfactorily in wet weather and none report trouble.

Corona (Question H-13)

No plant has observed any corona except *Miss. P.*, which gave a curve of corona losses reproduced in the drawing, Fig. 57.

General

Pa. W. & P. Note the following general comments:

Some of the changes which we have made, or contemplate making, in our equipment may be of interest as indicating the lines along which our operating experience and experiments are leading us.

A duplicate 11,000-volt generating station bus system was installed to replace the original group single bus system. This change made it easier to inspect and clean buses and connections, and made possible a better grouping of apparatus and reactances to limit short-circuit rush of current.

Reactances were installed between buses and transformers, and in sections of the buses. These reactances were rendered necessary by reason of the concentration of generating apparatus, giving peaks of over 70,000 kw., all of which power was sent over two transmission circuits to Baltimore. The destructive effects of short circuits backed by such large generator capacity were becoming serious.

Nicholson arresters and field-destroying devices were installed and a *fused air gap* arranged for the generating station to take a portion of these *heavy lightning discharges* which are *too great* for the *electrolytic arresters* to take care of. The Tirrill regulator equipment was abandoned and a storage battery with Keilholtz-Ricketts booster regulating system installed.

During the first period of operation the relay system was based upon the use of inverse time-element, reverse power, and definite time-element relays, set progressively higher in time from substation to power house. A great deal of experimental work, both in the laboratory and under operating conditions, was done in connection with the development of more accurate relays, but the results were not satisfactory. For a time, a modified Mertz-Price system was considered and partially installed, but was later abandoned for the system at present in use, which gives immensely superior results over the previous systems. With a steady increase of generator capacity concentrated on a few circuits, the destructive effects of arcs are becoming greater, so that a short circuit, which previously, with a small generator capacity, could have been allowed to remain on for six or seven

seconds, now does too much damage in that time in the way of melting of conductors, etc., so that our experiments are now along the line of cutting down the length of time which a short circuit remains upon the system.

We attribute our freedom from sleet disturbances to the very heavy mechanical construction employed and the frequent spacing of anchor towers.

We are now building a second tower line to Baltimore on the same 100 ft. right of way strip, 50 ft. distant from the first tower line. The second tower line has the following improvements: the number of members to a tower is less than previously, decreasing handling, erection and inspection costs, and making possible a minimum thickness of material of 3/16 in. as against a previous minimum of 1/8 in. All bolts are 5/8 in. diameter as against ½ in. diameter for the previous towers; the smaller bolts are very likely to be overstressed in tightening. The middle crossarm of the new line is being lengthened so that the top and bottom conductors of a circuit will be in the same vertical plane while the middle conductor will be further away from the tower.

This is to take care of unequal sags due to unequal sleet loading. Such unequal sleet loading has actually been observed on our lines and was anticipated in the design of the first line, but so far the unequal loading has not been sufficient to interfere with service. The distance between the crossarm and the conductor just above was such that on the old line buzzards when raising their wings to fly would ground the circuit; in the new line, a greater distance between crossarm and conductor above has been arranged for. In the first line steel tripod foundation stubs were used for the suspension towers; in the new line, all foundation stubs are of concrete. Interchangeability of bolts and certain members has been provided for in the new towers, which makes easier work of erection of the towers in the way of distribution of material and assembly.

In the first line as originally built there was a very considerable arcing over of the insulators due to lightning. A very complete record was kept covering the location of the disturbances, the phases upon which disturbances occurred, insulators cracked, etc. During the following year additional insulator units were added on one circuit over those two sections of the transmission line which had suffered most the previous year and a careful record again kept of the effect of lightning. These records indicated that there were no spill-overs during the second year on those

sections where additional insulator units had been cut in, except in one case where the discharge had jumped from conductor to crossarm below; this clearance distance having been decreased by the additional insulator units. Then additional strain and suspension insulator units were cut in on both circuits, so that at present No. 1 circuit has seven instead of five insulator units and eight instead of six strain units. Circuit No. 2 has six instead of five insulator units and seven instead of six strain units. The improvement, as regards lessened lightning spill overs, during the time the more heavily reinforced lines have been in service, has been marked.

The first transmission line was equipped with a single ground wire. Our experience has not indicated that this ground wire has been of any benefit in preventing disturbances. In order to establish the matter a little more definitely, the new transmission line is being equipped with two ground wires placed above and outside of the upper power conductors. The ground wire on the first line was originally strung so tight as to cause considerable trembling of the towers and it was necessary to cut in additional ground wire to increase the ground wire sag. This was done during operation without interfering with service.

Drawings

The following cuts are reproduced from drawings, charts and photographs submitted by the various reporting companies. In most cases the drawings have been redrawn to eliminate unnecessary detail and to consolidate the useful information embodied. The significance of each drawing may be obtained from its title, combined with the legends or other information on the face of the drawing. In all cases except one the name of the company furnishing the information is noted.

A number of valuable maps, charts, and photographs were received which could not be readily reproduced. These are open to the inspection of members of the Institute at New York headquarters. The Secretary will, where feasible, furnish copies for cost* on application. A list of some of the more valuable matter not reproduced follows:

Geographical Maps. Gt. Wn. P.; Yad. R. P.; Mex. L. & P., Ap.. P.; Sou. S. P.; Niag. L. & O. P.; Port. R. L. & P.; Mt. Wh'y P. & E.; X.

*In case of blue-prints retracing will generally be necessary.

Line Circuit Diagrams. *Mex. L. & P.; *Pa. W. & P.; *Niag. L. & O. P.; W'n St's. G. & E.; C. N. P.; Mt. Wh'y P. & E.; *Pug. S. T. L. & P.

Design Drawings of Steel Towers with Details. Miss. R. P.; Yad. R. P.; Niag. L. & O. P. (pipe towers); C. N. P. (pipe towers).

Detail Drawings of Wood Pole Construction. Niag. L. & O. P. (pin details of A-frame top); Wash. W. P. (two-pole braced "bridge" construction, 2 types one circuit line with one ground wire, 2 types one circuit line with no ground wire, angle towers with grounded wire guards); also W'n St's G. & E.; Pug. S. T. L. & P., (A-frame pole and pole-top switch); and X.

Miss. R. P. Tower foundation drawing.

Wash. W. P. Details of telephone line transposition. Detail of cable clamps and usual attachments for suspension insulators; wrought iron pin; details of extension of middle crossarm on steel towers added after erection.

Port. R. L. & P. Details of "jumper" at strain pole and insulator attachment; detail of outlet and the first span of the line at power house.

Niag. L. & O. P. Detail arrangement of room with transformers, electrolytic arresters and wiring.

Mt. Wh'y P. & E. Details of 33,000- and 6600-volt telephone and railway crossing.

ENGINEERING DATA SUB-COMMITTEE

PERCY H. THOMAS, *Chairman.*

W. A. CARLE	C. S. MCDOWELL
F. F. FOWLE	HAROLD PENDER
H. M. HOBART	E. B. ROSA
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O. A. KENYON	C. E. SKINNER
A. S. MCALLISTER	C. W. STONE

*Showing sectionalizing of busbars, types and locations of circuit breakers, etc.

YADKIN R

Cost Analysis, 9

Numbers Gr. Dv. Ju	Article	% of VII	Quantity	Units Used	
I	Towers, Standard & Special	33.8	748	Tower	
II	Insulators	8.6	"	"	
			27,751	Each	
III	Conductors	47.0	748	Tower	
			9,825	Cwt.	
IV	Ground Wire	2.5	748	Tower	
			1,372	Cwt.	
V	Telephone Line	7.4	748	Tower	
			3,078	Pole	
VI	Special Structures	0.7	748	Tower	
			27	Each	
VII	Total Material & Labor	100%	748	Tower	
VIII	Surveying	1.8	"	"	
IX	Right-of-Way	12.9	"	"	
X	Construction equipment (Net)	3.4	"	"	
XI	Commissary & Stores	5.0	"	"	
XII	General Expense	8.8	"	"	
XIII	Contingencies	0.2	"	"	
XIV	Engineering	7.1	"	"	
XV	Interest During Construction	3.0	"	"	
XVI	Total Construction	142%	748	Tower	

1. Construction Data

	Mi. Day
Excavation 15 June—24 Oct. 1911	0.86
Hauling Towers 4 July —19 Oct.	1.04
Assembling 5 July—24 Oct.	.99
Erection 7 July—24 Oct.	.97
Stringing Wire 9 Sept.—9 Dec.	1.33
Total Working days—152	0.53
Towers erected per day—Max. 19	
" " " " —Avg. 8	

Item	$
Material	
Labor	
Rt. of Way	
Other Exp	
Total	

3. Labor Rates

Rates per 10 hr. Day with Board—Assembling & Erecting gang $1.50 to $1.75. Linemen $2.00—Clearing Gang (colored) $1.25.

I	Towers	33.8% of VII	96	Mi. L
			748	Tower
A	Standard	92.6% of I	96	Mi. L
			736	Tower
1	Contract Price		736	Tower
2	Freight		736	"
			1,169	Tons
3	Handling and Hauling		736	Tower
			1,169	Tons
4	Erecting (inc. Setting Anchors)		736	Tower
5	Assembling		736	"
6	Digging Holes		736	"
7	Grading & Miscellaneous		736	"
B	Special and River Crossing	7.4% of I	12	"
1	Contract Price Delivered		12	"
2	Handling and Hauling		12	"
3	Erection		12	"
4	Assembling		12	"
5	Digging Holes		12	"
6	Tower Protection, Concrete		12	"
			115	cu. yds.
7	Erecting Wire and Insulators		12	Tower
II	Insulator	8.6% of VII	96	Mi. Line
			748	Towers
			27,751	Each
A	Contract Price	88.4% of II	27,751	"
B	Freight	5.4% " "	185	Ton
C	Handling and Hauling	2.9% " "	185	"
D	Erecting	3.3% " "	748	Tower
			27,751	Each
III	Conductors	47.0% of VII	96	Mi. Line
			748	Tower
A	Contract Price	90.4% of III	9,825	Cwt.
			748	Tower
B	Freight	4.7% " "	9,825	Cwt.
C	Handling & Hauling	1.8% " "	9,825	"
			748	Tower
D	Erecting	3.0% " "	748	"
E	Miscellaneous	0.1% " "	96	Mi. Line
			96	
IV	Ground Wire	2.5% of VII	96	Mi. Line
			748	Tower
A	Contract Price	94.1% of IV	1,372	Cwt.
			748	Tower
			1,372	Cwt.

VER POWER COMPANY

-mi., 100-kv., double-circuit line

Cost $	Totals: Per Mi. Line	Totals: % of Total	Group	Description and Explanations
169,740 35.80 .85 195.09 14.33 10.50 5.71 20.47 7.46 3.03 20.56	$1092 278 1520 .82 238 25	23.8 6.0 32.9 1.8 5.2 0.5	$104,995 26,718 145,954 7,831 22,981 2,256	This Line was built in two sections, Blewett Falls—Method (completed 24 Nov. 1911) and Method-So. Power Tie (completed 9 Dec. 1911)and extends over a 50' Right of Way, N. E. from the Blewett Falls Generting Sta., traversing a rolling, partly wooded country 30% of which is swampy or had to be cleared. It reaches the Method Sw. Sta. and turns N. W. tying in with the So. Power system midway between Raleigh and Durham. Between Blewett Falls and Method the avg. tower spacing is 690', 7.68 per mile with a max. span of 1455'. From Method to Durham avg. spacing is 680', 7.9 towers per mile and max. span 950'. 73' galv. steel stand. towers carry 2-100 KV. 3 bare circuits of No. 1/0 6 str. copper on 6 disc. unit suspension insulators Conductors are spaced 15'-0" horiz. and 9'-0" vert. Avg. haul of materials 3 3/4 miles. Line was constructed in Summer and Fall of 1911. Telephone line on separate right of way 102 miles long. Excavation for towers began 16 Oct. 1911; Wire stringing finished 27 Jan. 1912.
415	$ 3,235	70%	$310,738	
7.60 53.65 13.30 20.55 36.60 .90 29.43 13.40	59 419 119 160 285 7 229 97	1.3 9.1 2.6 3.5 6.2 0.2 5.0 2.1	5,691 40,214 11,443 15,384 27,375 670 22,014 9,271	
$591	$4,615	100%	$442,800	

2. Condensed Cost Data

per Mi.	$ per Tower	$ Total	%
2864	367.30	274,769	62.1
373	48.09	35,900	8.1
413	53.76	40,214	9.1
959	121.49	91,848	20.7
4613	$590.64	$442,800	100%

1002.00 146.40 1013.00 132.00 107.10 .285 .843 4.23 2.69 5.47 7.61 7.41 .540 645.00 403.00	78,831 284 3,103 4,020 5,162 5,486 365 4,828	97,251 7,747	$104,993	Standard Towers—Furnished by Milliken Bros. 73' from top of Tower to top of Stub. Price F. O. B. Sanford or equivalent. Freight charge for excess distance. Average haul 3.75 miles. Weight of Towers approx. 3100 lbs. and cost 3.5 c. per lb. By Shear Leg Method 20% rock excavating. Includes stump grubbing. Special dead end Tower (double) 2 double Towers with 25' extension legs. 3 angle Towers and 3 standard with special footings—Transportation across river by cableway.
4.53 31.35 14.50 13.58 117.50 12.24 62.10	52 376 175 163 1,408 745			Ere tion includes concrete footings. Mostly rock holes. Includes $864. for special concrete protection. 2 Lines ⅛ 7 str. stl. cable galv. & 12 line ⅛" C9 Str. cu. cld. steel.
278.00 35.80 .963 .833 10.21 4.15 1.17 .032		22,832 2,241 768 877	$26,718	No. 1113 Thomas—36 discs to standard towers.84 at angles on So. Power Line, 42 on angles Blewett Falls Line contract price $79.38 less 2% on Blewett Falls Line $79.38/C less 3% including clamps on So. Power Line. Hauled by Company teams, 20 crates to load.
1520.00 195.09 14.85 170.50 13.42 .704 .397 2.31 2.73 45.[illegible] 1.32		131,966 6,910 2,[illegible] 4,[illegible] 1,[illegible]	$145,954	6 lines 1/0-7 strand copper cable. Weight 1710 lbs/mi Bar copper price 12 1/8 c. per lb. Drawing 1 1/4 c. per lb. Price includes splicing sleeves and protection sleeves. Includes 20 empty reels not returned.
61.30 10.20 5.75 1.79 4.23		6,[illegible]	$7,[illegible]	3/8" double galv. strand cost about 1415 per mi. Contract price Blewett Falls L. $1.30 per C ft. less .2; $4.4.[illegible] F.O.B. Raleigh points. So. Power line $1.[illegible] /C ft. same delivery.

PAGE GRO

	C	Hauling & Hauling	[illegible]	96
	D	Erection	9.2% " "	96
V		Telephone Line	7.4% of VII	96
				748
				3,078
	A	Poles	21.9% of V	3,078
	B	Cross Arms	4.6% " "	3,115
	C	Insulators & Pins	.8% " "	6,230
	D	Hardware	8.2% " "	3,078
	E	Digging, Framing, Erect.	13.6% " "	3,078
	F	Guy Cable	.5% " "	15
	G	Conductors	30.4% " "	3,078
	H	Hauling & Handling	9.8% " "	3,078
	I	Stringing Wire	5.1% " "	3,078
	J	River Crossing	0.2% " "	4
	K	Telephone Booths	4.9% " "	10
VI		Special Structures	.07% of VII	96
				748
	A	Telephone & Highway Prot.	5.4% of VI	5
	B	Miscellaneous	45.5% " "	21
	C	Sectionalizing Tower	49.1% " "	1
	1	Contract Price Delivered		1
	2	Handling & Hauling		1
	3	Erecting		1
	4	Assembling		1
	5	Digging Holes		8
	6	Wire Installation		1
VII		Total Material & Labor	100%	96
				748
VIII		Surveying	1.8% of VII	96
	A	Salaries	48.6% " VIII	"
	B	Tra ing Expenses	12.6% " "	"
	C	Equipment	5.5% " "	"
	D	Miscellaneous Supplies	0.5% " "	"
	E	" Expense	0.3% " "	"
	F	Telephone Line	32.5% " "	102
IX		Right-of-Way	12.7% of I-VIII	96
	A	Agent	7.7% " IX	"
	1	Salaries		"
	2	Traveling Expenses		"
	3	Miscellaneous		"
	B	Legal Expenses	5.4% of IX	"
	1	Salaries		96
	2	Traveling Expenses		"
	C	Purchase-Price-Easements	33.2% of IX	"
	D	Damages	2.5% " "	"
	E	Clearing	22.8% " "	"
	F	Telephone Line	28.4% " "	102
X		Construction Equip't.	3.2% of I-IX	96
	A	Wagons & Horses	22.7% of X	"
	B	Tents & Camp Equip.	24.0% " "	"
	C	Rigging & Tools	20.4% " "	"
	D	Moving Camp	22.8% " "	"
	E	Roads	2.3% " "	"
	F	Charges To Tel. Line	7.1% " "	102
XI		Commissary & Stores	4.2% of I-X	96
	A	Board & Lodging	65.9% " XI	
	1	Supplies		
	2	Labor		
	3	Outside Board		
	4	Credits		
	B	Commisary Operation	10.9% of XI	
	1	Supplies		
	2	Labor		
	3	Credits		
	C	Charged to Tel. Line	23.2% of XI	
XII		General Expense	7.1% of I-XI	96
	A	Salaries	48.1% " XII	
	B	Traveling Expenses	7.8% " "	
	C	Office Rent	0.3% " "	
	D	" Equipment	2.7% " "	
	E	Telephone & Telegraph	2.2% " "	
	F	Liability & Injuries	4.4% " "	
	G	Livery	4.06% " "	
	H	Automobile	[illegible] " "	

		722		
			$22,981	Material & Labor on telephone L ne. 101.92 Mi. at $225.35/Mi. & $7.46/Pole.
		5,040		2850—25′; 158-30′; 35-35′; 32—45′; 3—50 Juniper
		1,049		3½x4½x4′—12c. ex. f. o. b. Fytville. incl. tr. creos. oil.
		175		No. 1094—$25/M; Locust pins $13.25/M.
		1,874		Braces, bolts, screws, washers, etc.
		3,124		Poles spaced 169.5 ft. avg. Excav. begun 16 Oct. 1911.
		124		5/16" Ex. galv. Str. $2.25 C. Ft.
		6987		2—No. 8 B. & S. H. O. copper clad.
		2,251		Work on line not continuous, participated in V completed 27 Jan. 1912. by 2 separate crews.
		1,167		
		54		2—60′ poles N. side; 2—45′ poles S. side at river.
		1,136		Incl' Repair material.
			$2,256	Includes Sanford Sect onalizing Tower.
		122		Temporary Labor at R. R. crossings.
		1,028		Disconnecting switches and labor.
		1,106		Special Tower at Sanford.
	565			
	6			
	118			
	151			
	17			
	249			
			$310,738	70.2% of Total Cost.
			$5,691	Does not include cost of original survey made by Lockwood, Greene & Co.
		2,767		
		719		
		311		
		26		
		16		
		1,852		
			$40,214	50′ Right-of-Way—Practically none donated.
		3,103		Portions of Right-of-Way—Practically 100′, & ab. 1 mil 30′
	2,140			
	853			From Blewett Falls to Method 1072 acres avg. cost per acre for easements $10.30;
	110			
		2,151		From Method to So. Power Tie 100 acres avg. cost per acre for easements $23.37. Avg. purchase cost over total line—$11.42 per acre.
	730			
	1,421			
		13,382		
		993		
		9,177		About 30% clearing heavy & swampy.
		11,408		Includes $1620. for clearing.
			$11,443	Net Cost.
		2,601		Depreciation
		2,844		"
		2,333		"
		2,590		
		258		
		817		Depreciation
			$15,384	Net Cost.
		10,137		
	11,559			
	5,765			
	604			
	(7791)			
		1,671		
	3,093			
	445			
	(1867)			
		3,576		
			$27,375	
		13,173		
		2,133		
		75		
		747		
		594		
		1,214		
		1,090		
		1,300		
		1,423		

LIST OF MATERIAL FOR ONE COMPLETE TOWER. (See Fig 1).

No.	Shape	Size	Length Pt.	Length In.	Mark	Remarks	Weight in Lb.
1	L	3 x 3 x 3/16"	27–	8 5/16	C–1		102.7
3	L[5]	3 x 3 x 3/16	27–	8 5/16	C–2		308.2
1	L	2½ x 2½ x 3–16	21–	10	C–3		74.0
3	L[5]	2½ x 2½ x 3–16	21–	10	C–4		222.0
1	L	2½ x 2½ x 1/8	18–	8 3/16	C–5		38.8
3	L[5]	2½ x 2½ x 1/8	18–	8 3/16	C–6		116.6
4	L[5]	2½ x 2½ x 1/8	6–	8 1/8	C–7		55.6
2	L[5]	2½ x 2½ x 1/8	6–	4½	A–1		26.5
2	L[5]	2½ x 2½ x 1/8	6–	4½	A–2		26.5
4	L[5]	2½ x 2½ x 1/8	6–	4½	A–3		53.0
4	L[5]	2½ x 2½ x 1/8	6–	4½	A–4		53.0
4	Flats	1½ x 3/16	7–	5 9/16	A–5		23.8
4	Flats	1½ x 3/16	7–	6 3/8	A–6		24.0
4	Flats	1½ x 3/16	9–	4¾	A–7		30.0
6	T[6]	4½ x 3 x 8.4	0	5 3/16	A–8		21.8
4	L[5]	1½ x 1½ x 1/8	25	5 7/8	W–1		125.4
4	L[5]	1½ x 1½ x 1/8	25	5 7/8	W–2		125.4
8	L[5]	1½ x 1½ x 1/8	2	4½	W–3		19.2
8	L[5]	1½ x 1½ x 1/8	5	7 3/8	W–4		45.3
8	L[5]	1½ x 1½ x 1/8	4	8 3/8	W–5		37.9
16	L[5]	1½ x 1½ x 1/8	7	0 3/8	W–6		113.6
4	L[5]	2½ x 2½ x 1/8	10	11¾	W–8		100.5
8	L[5]	1½ x 1½ x 1/8	11	8 9/16	W–9		115.2
8	L[5]	1½ x 1½ x 1/8	10	3 15/16	W–10		101.6
4	L[5]	1½ x 1½ x 1/8	9	4 9/16	W–11		46.1
2	L[5]	2½ x 2½ x 3/16	9	4 9/16	W–12		57.6
8	L[5]	1½ x 1½ x 1/8	8	4 1/16	W–13		82.0
6	L[5]	1¾ x 1¾ x 1/8	7	4 5/8	W–14		63.8
4	L[5]	2 x 2 x 1/8	4	5	W–15		29.1
4	L[5]	1¾ x 1¾ x 1/8	6	2 31/32	W–16		36.0
4	L[5]	1¾ x 1¾ x 1/8	6	2 31/32	W–17		36.0
4	L[5]	1¾ x 1¾ x 1/8	6	2 31/32	W–18		36.0
4	L[5]	1¾ x 1¾ x 1/8	6	2 31/32	W–19		36.0
16	L[5]	1½ x 1½ x 1/8	6	2 1/8	W–20		99.8
2	L[5]	2 x 2 x 1/8	4	5	W–21		14.6
2	L[5]	2 x 2 x 1/8	4	5	W–22		14.6
4	L[5]	1½ x 1½ x 1/8	4	3¾	W–23		21.2
4	L[5]	1½ x 1½ x 1/8	6	1½	B–1		24.7
2	Flats	1½ x 3/16	15	8 9/16	B–2		24.9
6	Flats	1½ x 3/16	6	2¾	B– 3		29.8
38	B. H. Step Blts ⅝" ϕ		0	5 1/8	Hex. Nut 1⅛"Thrd.		16.9
38	Pieces ¾" ϕ Gas Pipe.		0	4	Ends Square		10.6
38	Washers 1 3/8" ϕ		9/16"	ϕ Hole	No. 12 Gage		1.9
390	Bolts ¾" ϕ 1¾" Lnd.		¾"	Min. Grip Sq. Hd. Hex. Nut.			6.8
4	Bolts ⅝" ϕ 2"		Lng.	7/8 Min. Grip		Sq. Hd. Hex Nut	.9
1	Ground Wire Clamp						7.4
2	L[5]	1¾ x 1¾ x 1/8	7	4 5/8	W–24		21.3
2	L[5]	2½ x 2½ x 3/16	9	4 9/16	W–25		57.6
6	Insulator Hooks						8.7
		Total	Net Weight of one Standard Tower				2814.9
4	L[5]	3 x 3 x ¾"	8	0	S–1		156.8
4	C[4]	12"–20½"	1	6	S–2		123.0
8	Pls.	8 x ½	0	2	S–3		16.4
						Grand Total	3111.1

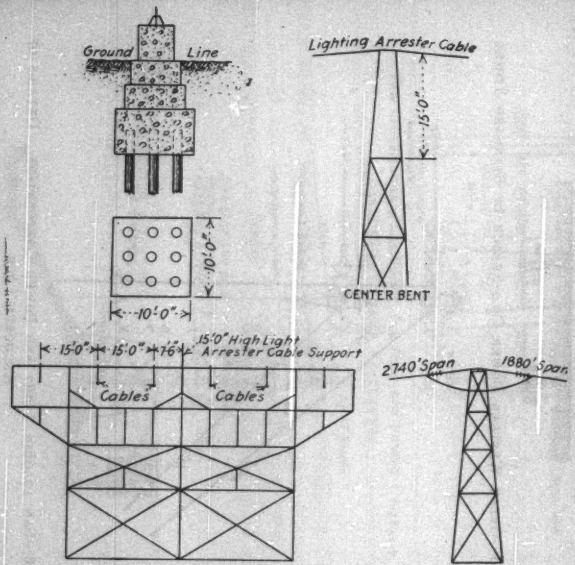


FIG. 3—GREAT WESTERN POWER CO.—TOP OF SPECIAL TOWER AT WEST ISLAND

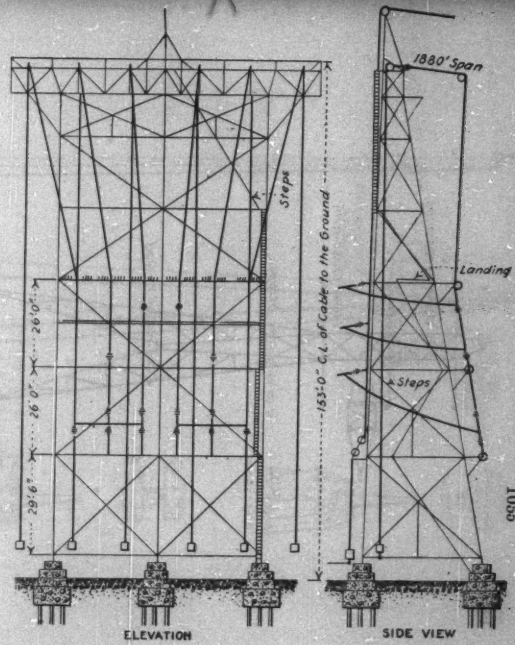


FIG. 4—GREAT WESTERN POWER CO.—SPECIAL TOWER AT KELLY ISLAND

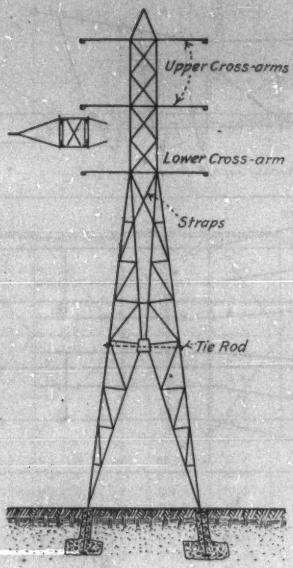


FIG. 5—GREAT WESTERN POWER CO.—SKETCH OF STANDARD TOWER

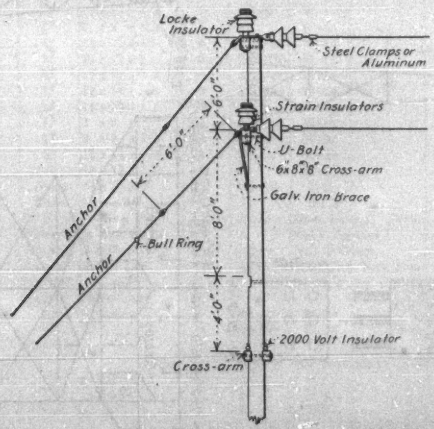


FIG. 6—SAN JOAQUIN LIGHT AND POWER CORPORATION. DETAILS OF ANCHORED POLE

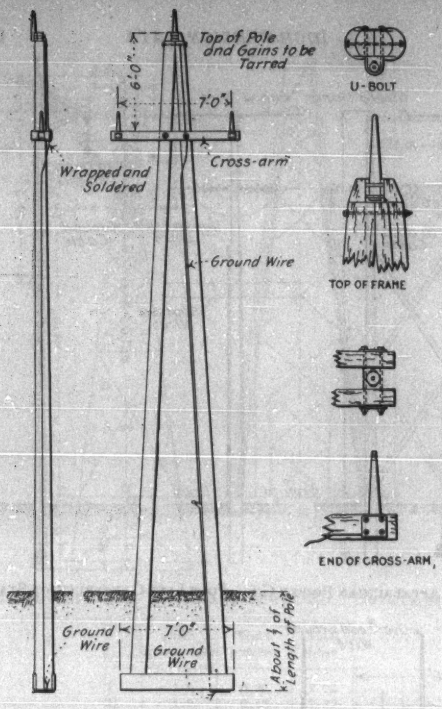


FIG 7—NIAGARA, LOCKPORT AND ONTARIO POWER COMPANY. STANDARD A-FRAME STRUCTURE.

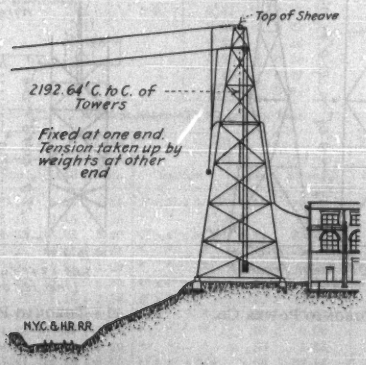


FIG. 8—CANADIAN NIAGARA POWER CO. TOWER AT NIAGARA CROSSING

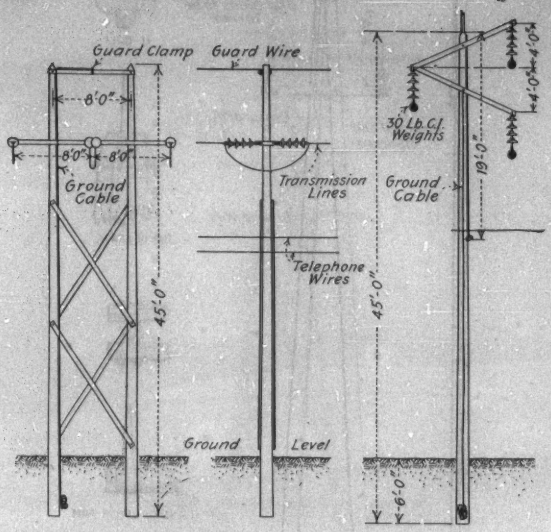


FIG. 9—APPALACHIAN POWER CO. POLE LINE CONSTRUCTION STANDARDS

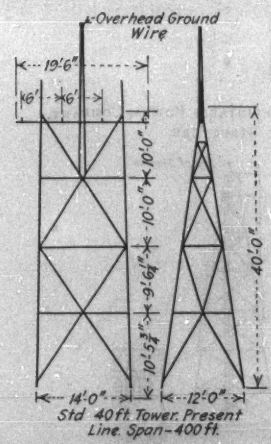


FIG 10—TORONTO POWER CO.

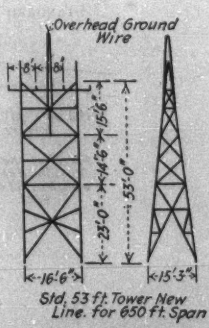


FIG. 11—TORONTO POWER CO.

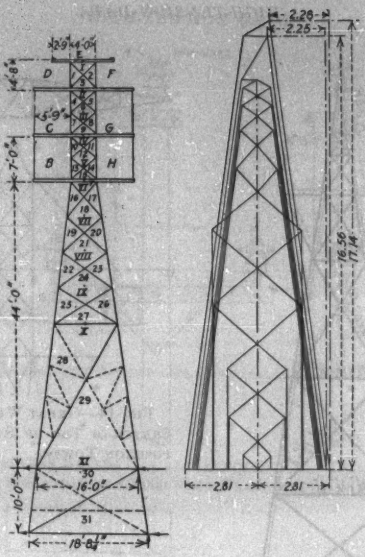


FIG. 12—PENNSYLVANIA WATER AND POWER CO. DETAILS OF TOWER

	Load from wire	Wind pressure	Total Load
I	1.9	0.22	2.12
II	1.9	0.43	2.33
III		0.14	0.14
IV	1.9	0.42	2.32
V		0.14	0.14
VI	1.9	0.47	2.37
VII		0.22	0.22
VIII		0.23	0.23
IX		0.25	0.25
X		0.49	0.49
XI		0.64	0.64

Wind pressure = 13 lb. per sq. foot.

Location	Load	Load per. sq. inch.	Section	Area	Ultimate Strength	Factor of Safety
H-11	6.28	5.65	3" x 3" x 3/16"	1.11	39.86	7.
H-14	9.15	8.25	" " "	"	"	4¼"
I-20	14.08	5.85	4" x 4" x 5/16"	2.41	35.92	6
I-23	15.04	6.25	" " "	"	"	5¾
I-26	15.94	6.62	" " "	"	"	5½
I-29	10.2	6.36	4" x 4" x 3/8"	2.86	35.51	5½
15-17	1.18	2.36	2" x 2" x ¼"	.50	13.27	5½
18-20	.85	6.70	" " "	.50	10.92	6½
21-23	.69	.38	" " "	.50	9.00	6½
24-26	.60	1.20	" " "	.50	5.85	5
I-31	19.15	6.70	4" x 4" x 3/8	2.86	32.51	5

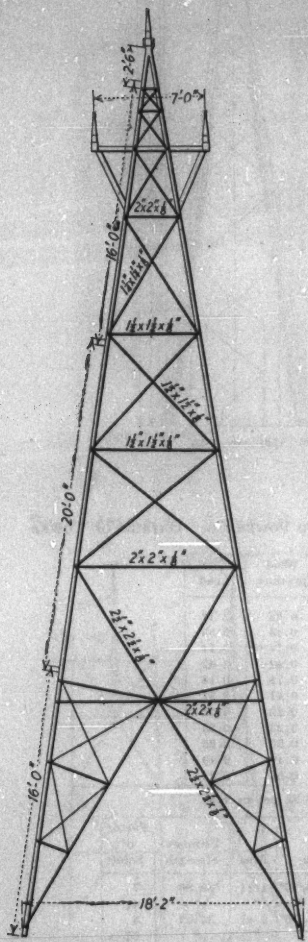


FIG. 13—NIAGARA, LOCKPORT AND ONTARIO POWER CO. 49-FOOT SINGLE AND DOUBLE PIN TOWER

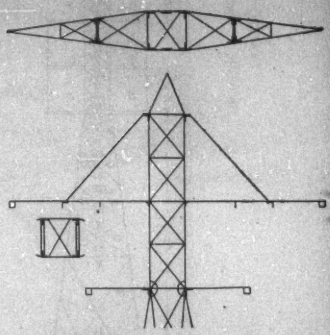


FIG. 14—GREAT WESTERN POWER CO. SKETCH OF TOP OF REINFORCED TRANSPOSITION TOWER.

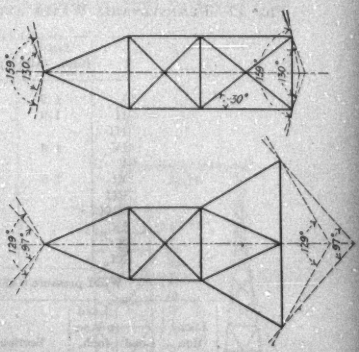


FIG. 15—MISSISSIPPI RIVER POWER CO. SPECIAL CROSSARMS FOR ANGLE TOWER

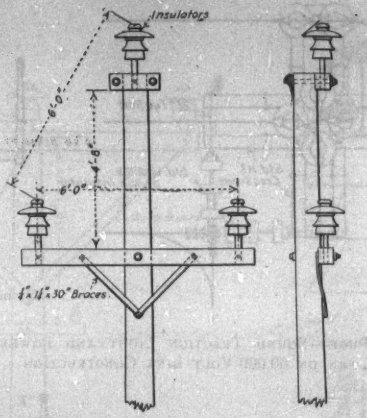


FIG. 16—WESTERN STATES GAS AND ELECTRIC CO. TRIANGULAR CONSTRUCTION OF 60,000-VOLT TRANSMISSION LINE.

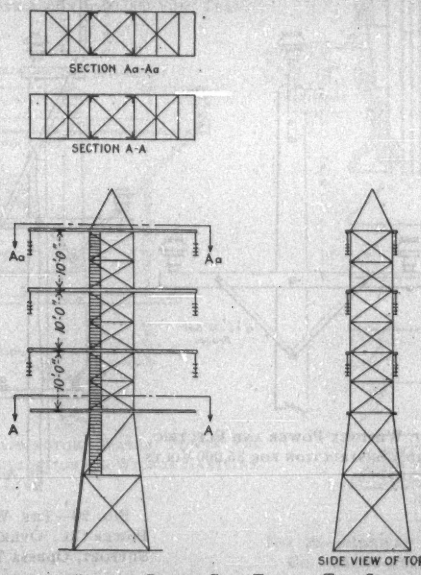


FIG. 17—GREAT WESTERN POWER CO. TOPS OF TWO SPECIAL TOWERS AT ISLETON

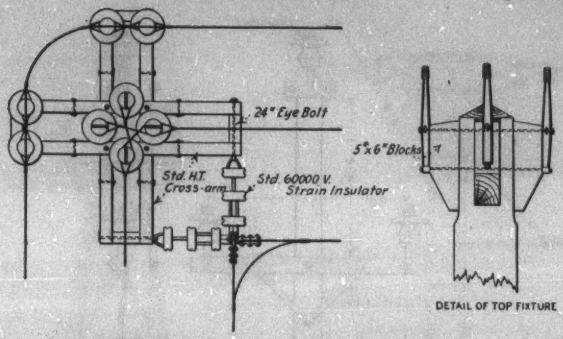


FIG. 18—PUGET SOUND TRACTION LIGHT AND POWER CO. SQUARE TURN ON 60,000-VOLT LINE CONSTRUCTION

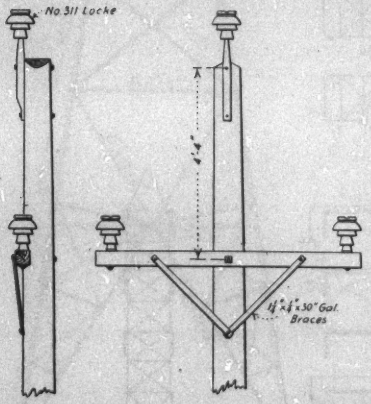


FIG. 19—MT. WHITNEY POWER AND ELECTRIC CO. STANDARD CONSTRUCTION FOR 35,000 VOLTS

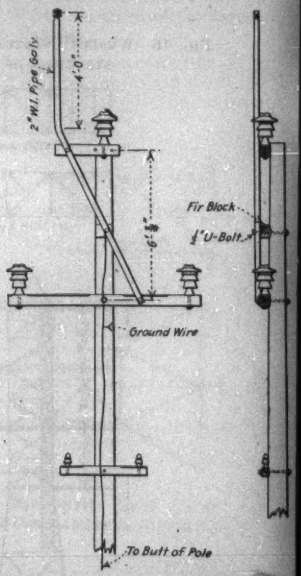


FIG. 20—THE WASHINGTON WATER POWER CO. OVERHEAD GROUND WIRE SUPPORT, ODESSA TRANSMISSION LINE

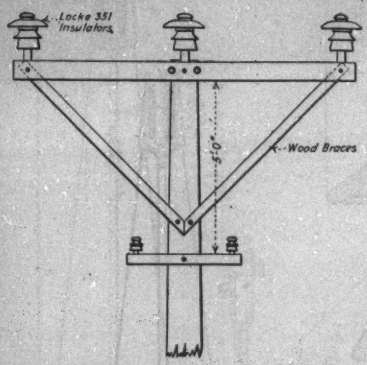


FIG. 21—WESTERN STATES GAS AND ELECTRIC CO. FLAT CONSTRUCTION OF 60,000-VOLT TRANSMISSION LINE.

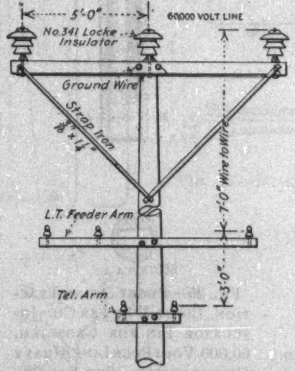


FIG. 22—WASHINGTON WATER POWER CO. POLE TOP CONSTRUCTION FOR WILBUR HARTLINE TRANSMISSION LINE

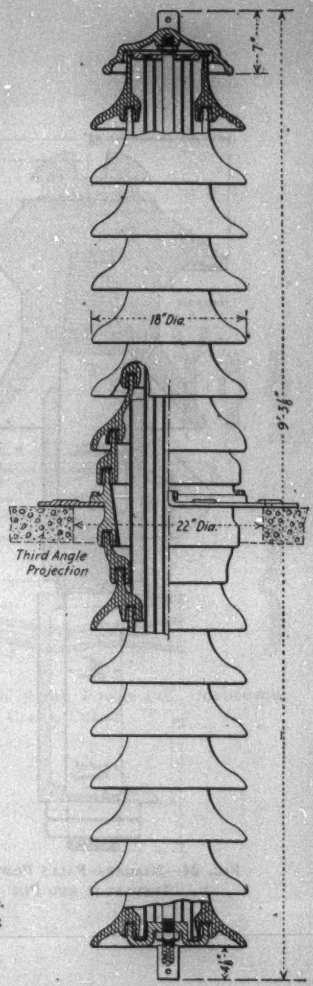


FIG. 23—MEXICAN LIGHT AND POWER CO. 85,000-VOLT ROOF BUSHING

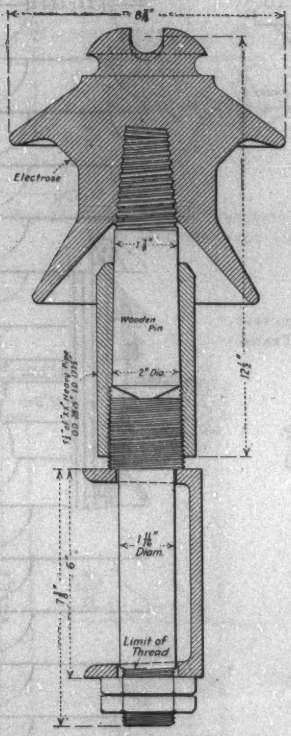


FIG. 24—NIAGARA FALLS POWER CO. INSULATOR AND PIN

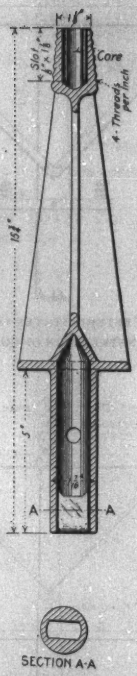
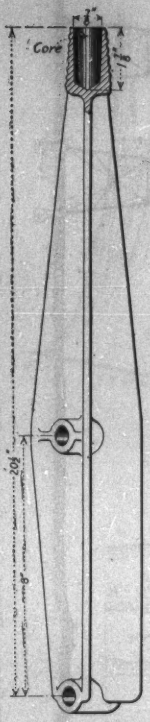


FIG. 25—PUGET SOUND TRACTION, LIGHT & POWER CO. INSULATOR PIN FOR CROSSARM, 60,000-VOLT POLE LINE, HEAVY CONSTRUCTION. SEE FIG. 26



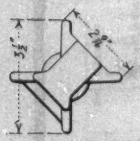


FIG. 26—PUGET SOUND TRACTION, LIGHT AND POWER CO. INSULATOR PIN FOR POLE TOP, 60,000-VOLT POLE LINE, HEAVY CONSTRUCTION. SEE FIG. 25

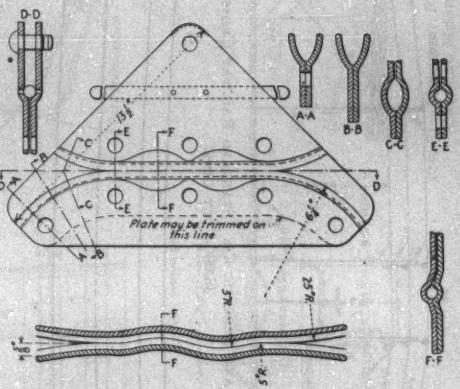


FIG. 27—MISSISSIPPI RIVER POWER CO. CONDUCTOR CABLE CLAMP

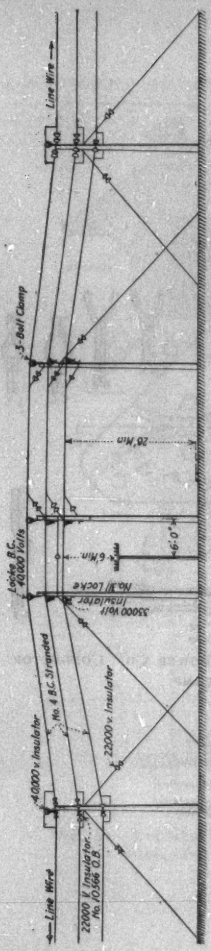


FIG. 28—MT. WHITNEY POWER AND ELECTRIC CO. STANDARD RAILWAY CROSSING NO. 3 FOR 6600- AND 33,000-VOLT LINE.

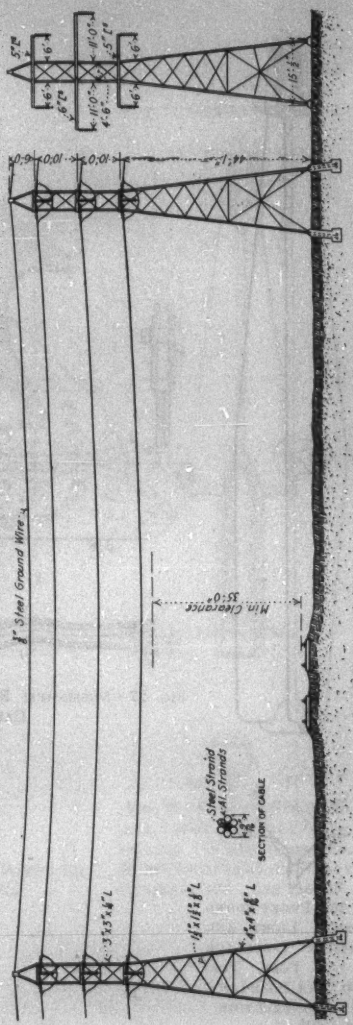


FIG. 29—SOUTHERN SIERRAS POWER CO. PROPOSED CONSTRUCTION AT RAILWAY CROSSINGS

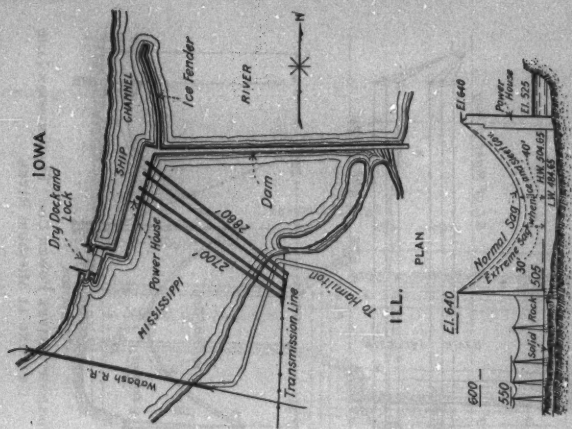


FIG. 31—MISSISSIPPI RIVER POWER CO. TRANSMISSION LINE CROSSING MISSISSIPPI RIVER AT KEOKUK, IOWA

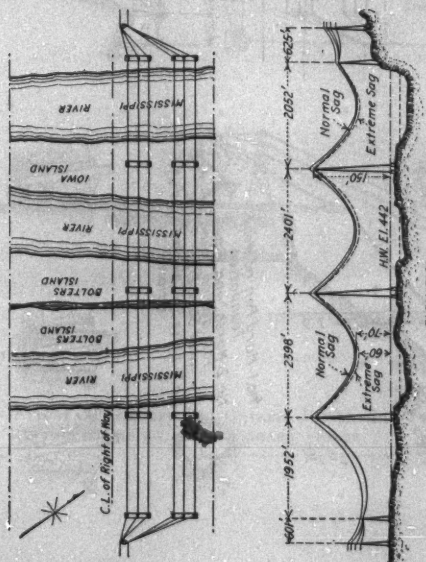


FIG. 30—MISSISSIPPI RIVER POWER CO. TRANSMISSION LINE CROSSING MISSISSIPPI RIVER AT IOWA ISLAND

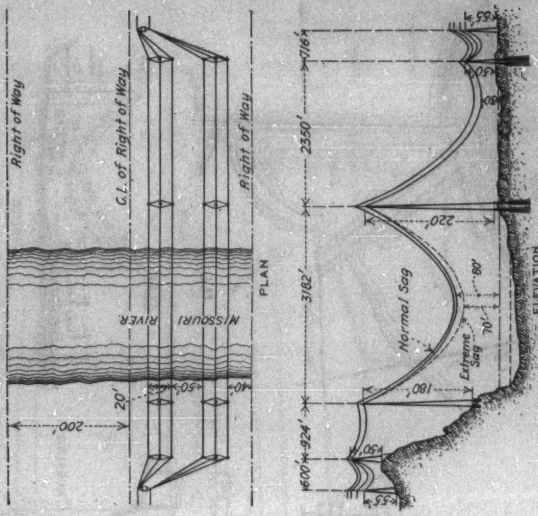


Fig. 33—Mississippi River Power Co. Transmission Line Crossing at Missouri River

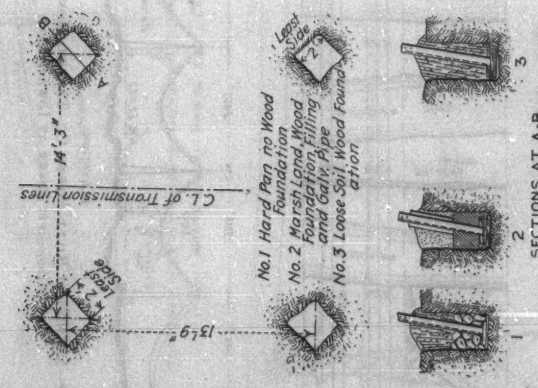


Fig. 32—Mexican Light and Power Co., Ltd. Plan and Sections of Tower Foundations

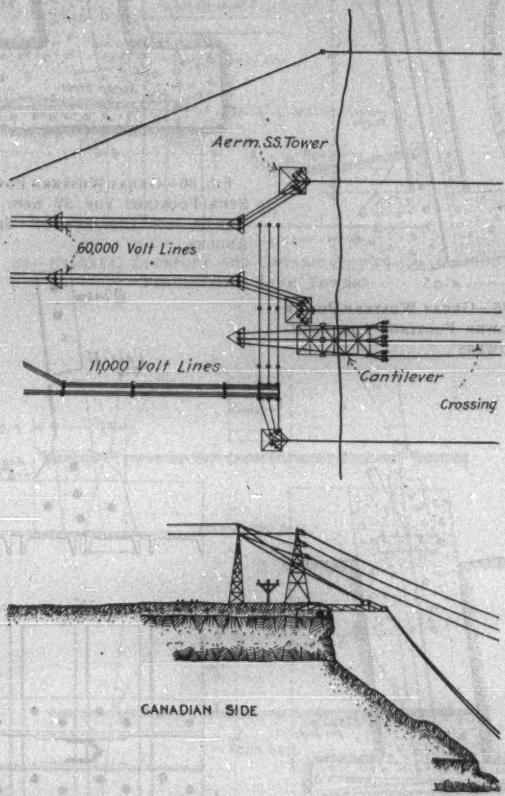


FIG. 34—NIAGARA, LOCKPORT AND ONTARIO POWER CO. PROFILE OF REVISED CROSSING OVER NIAGARA GORGE

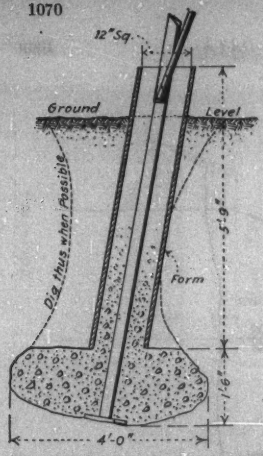


FIG. 35—GREAT WESTERN POWER CO. TOWER FOOTINGS FOR STANDARD TOWERS

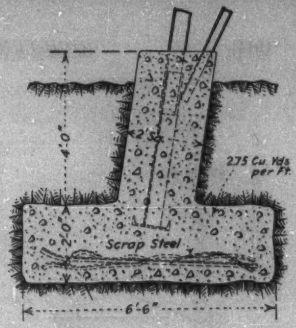


FIG. 36—GREAT WESTERN POWER CO. STUB FOOTINGS FOR 37 DEG. ANGLE TOWER ON COMPRESSION SIDE OF ANGLES

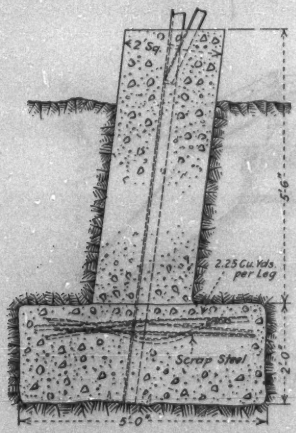
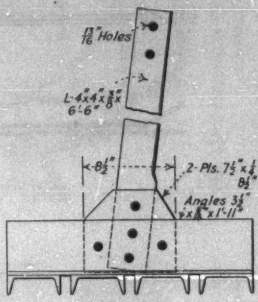


FIG. 37—GREAT WESTERN POWER CO. FOOTINGS FOR ANCHOR TOWER ON TENSION SIDE OF ANGLES



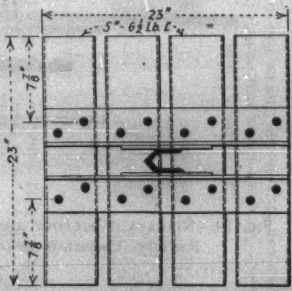


FIG. 38—WASHINGTON WATER POWER CO. GRAVEL ANCHOR FOR STEEL TOWERS

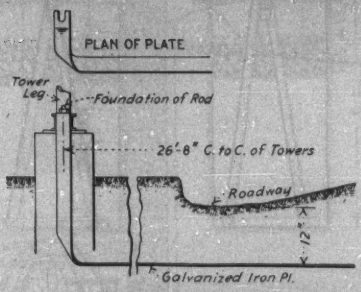


FIG. 39—NIAGARA, LOCKPORT AND ONTARIO POWER CO. GROUND FOR TRANSMISSION LINE TOWERS

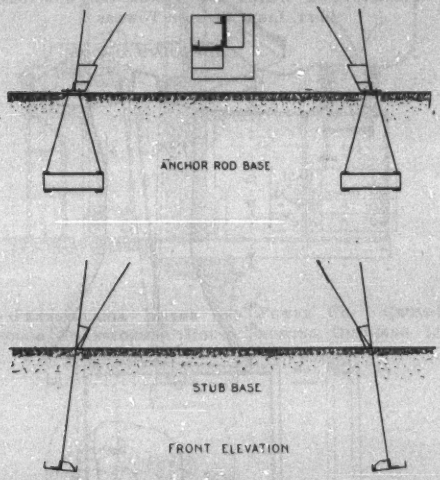


FIG. 40—GREAT WESTERN POWER CO. BASES FOR 37-DEG. ANGLE TOWER

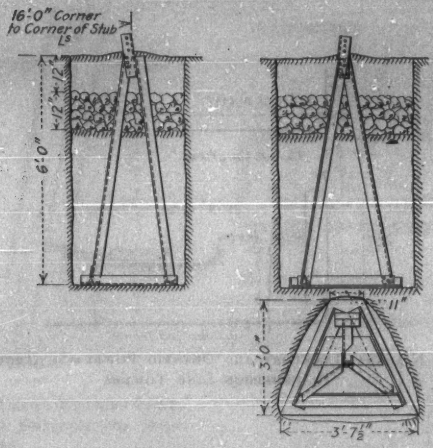
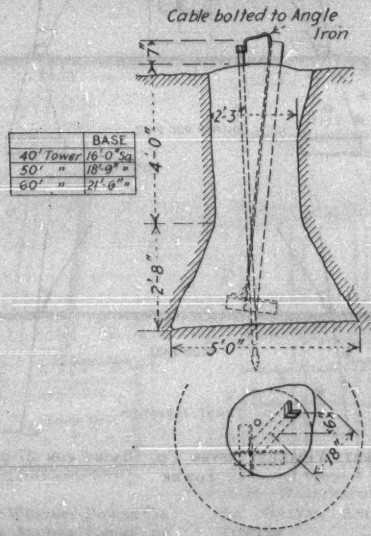


FIG. 41—PENNSYLVANIA WATER AND POWER CO. FOUNDATION FOR 40-FT. LIGHT SECTION TOWERS



	BASE
40' Tower	16'-0" Sq.
50' "	18'-9" "
60' "	21'-6" "

FIG. 42—PENNSYLVANIA WATER AND POWER CO. CONCRETE FOUNDATION FOR HEAVY TOWERS

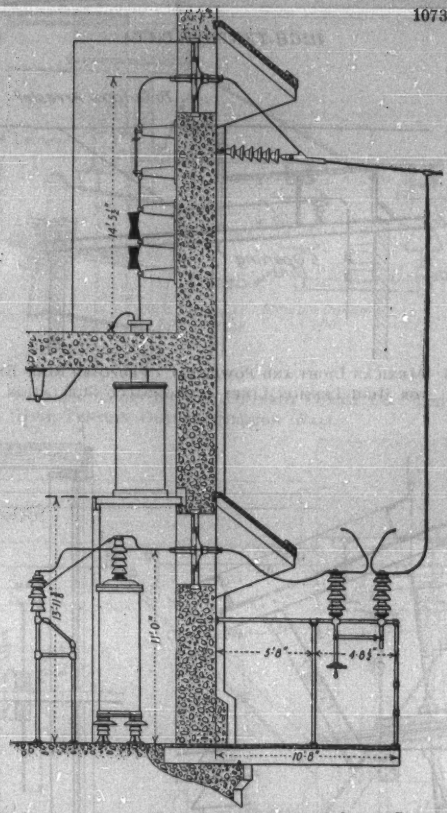


FIG. 43—PENNSYLVANIA WATER AND POWER CO. CROSS-SECTION THROUGH TRANSFORMER HOUSE, SHOWING OUTGOING LINE

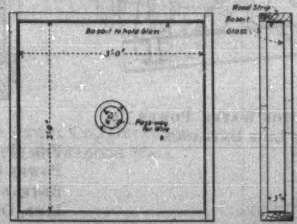


FIG. 44—WESTERN STATES GAS AND ELECTRIC CO. STANDARD EXIT FOR TRANSMISSION WIRES AT SUBSTATIONS

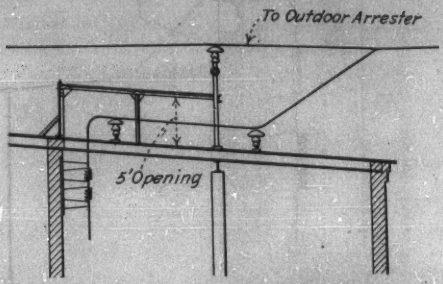


FIG. 45—MEXICAN LIGHT AND POWER CO. PROPOSED ROOF ENTRANCE FOR HIGH-TENSION LINES AT NONOALCO SUBSTATION

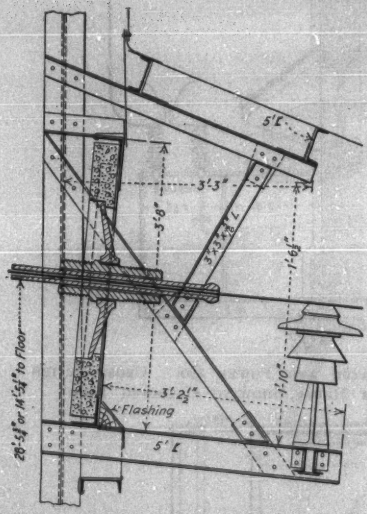


FIG. 46—WASHINGTON WATER POWER CO 60,000-VOLT LINE ENTRANCE

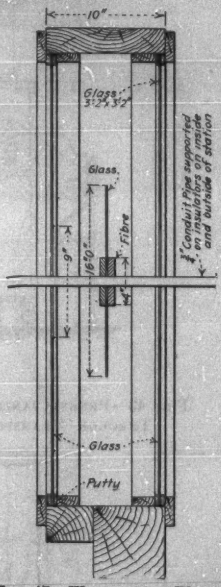


FIG. 47—WASHINGTON WATER POWER CO. DETAIL OF WALL ENTRANCE FOR HIGH-TENSION LINE, ODESSA SUBSTATION

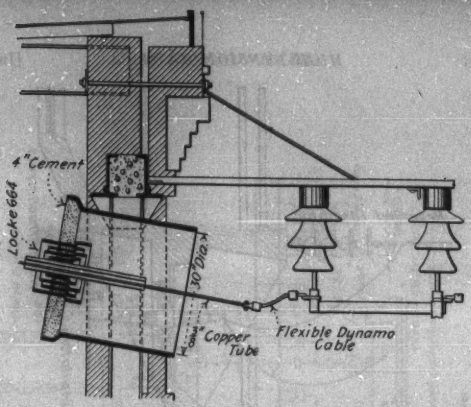


FIG. 48—NIAGARA, LOCKPORT AND ONTARIO POWER CO. DETAIL OF HIGH-TENSION OUTLET THROUGH WALL

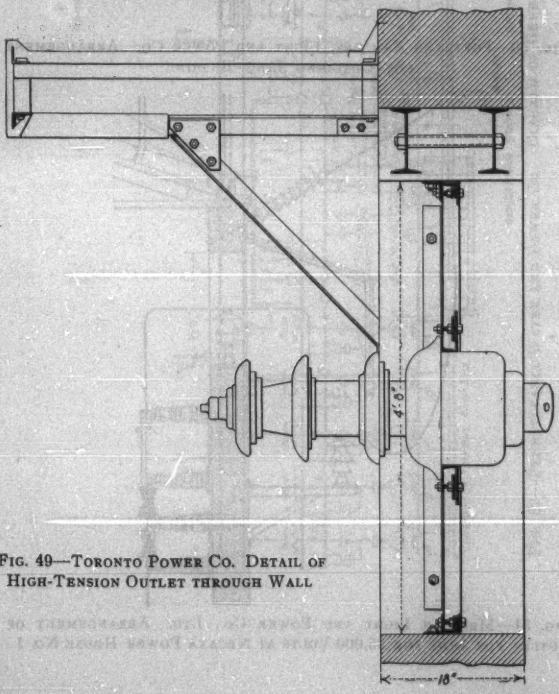


FIG. 49—TORONTO POWER CO. DETAIL OF HIGH-TENSION OUTLET THROUGH WALL

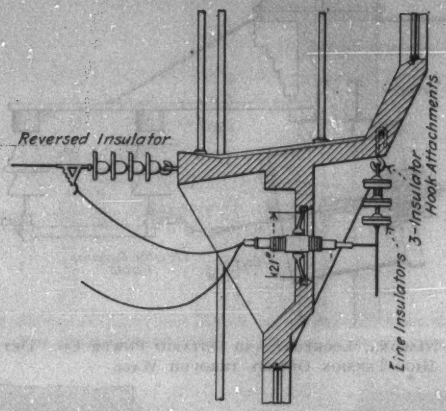


FIG. 50—PORTLAND RAILWAY, LIGHT AND POWER CO. ARRANGEMENT OF OUTGOING LINE BUSHING

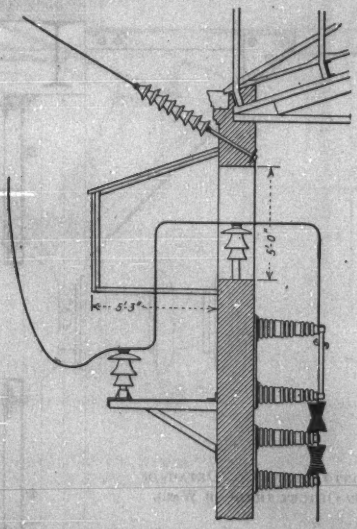


FIG. 51—MEXICAN LIGHT AND POWER CO., LTD. ARRANGEMENT OF OUTLET FOR LINE FOR 85,000 VOLTS AT NECAXA POWER HOUSE NO. 1

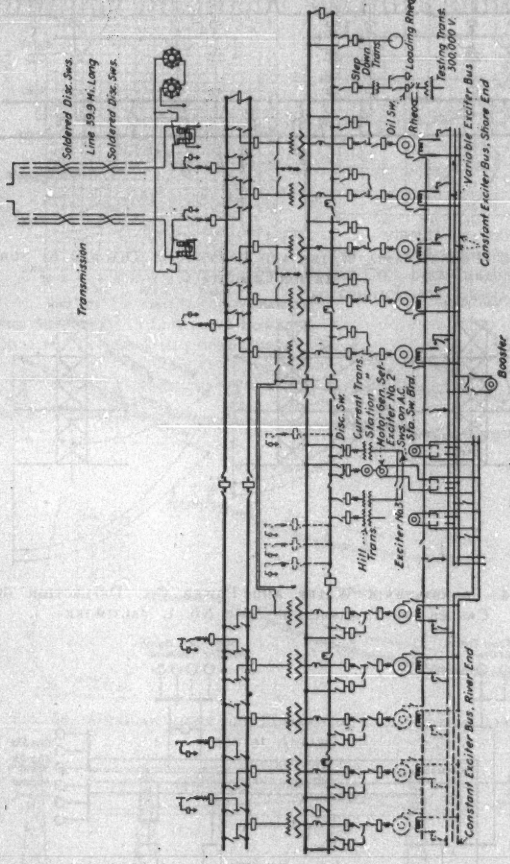


FIG. 52—PENNSYLVANIA WATER AND POWER CO. DIAGRAM OF GENERATING AND TRANSMISSION SYSTEM

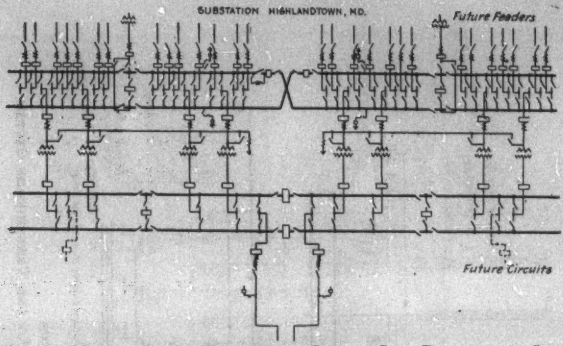


FIG. 53—PENNSYLVANIA WATER AND POWER CO. DIAGRAM OF SUBSTATION CIRCUITS

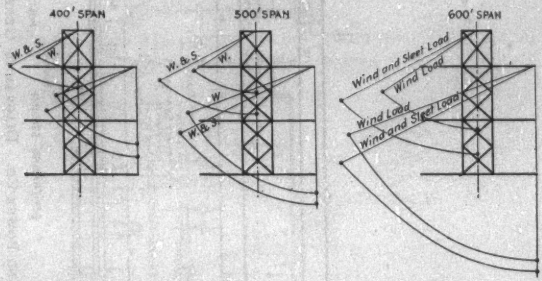


FIG. 54—PENNSYLVANIA WATER AND POWER CO. DEFLECTION OF CABLES FOR TRANSMISSION LINE NO. 1, BALTIMORE

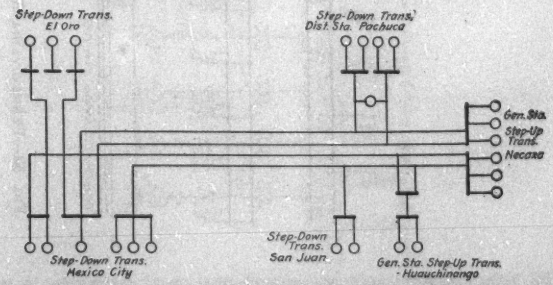


FIG. 55—MEXICAN LIGHT AND POWER CO., LTD. DIAGRAM OF HIGH-TENSION TRANSMISSION LINES

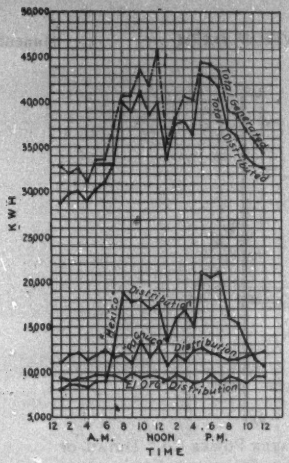


FIG. 56—MEXICAN LIGHT AND POWER CO., LTD. TYPICAL DAILY LOAD CURVE

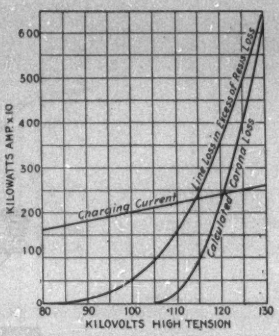


FIG. 57—MISSISSIPPI RIVER POWER CO. LINE CHARGING CHARACTERISTICS AND CORONA LOSSES

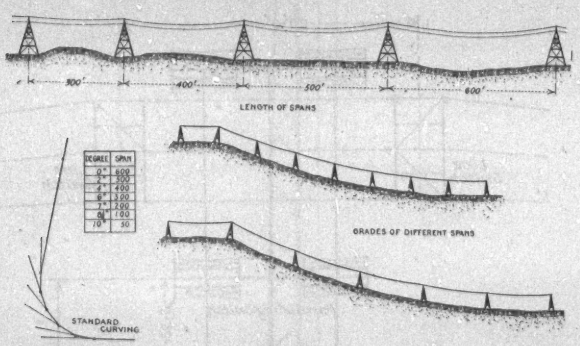


FIG. 58—MEXICAN LIGHT AND POWER CO., LTD., VERTICAL AND HORIZONTAL ANGLES.

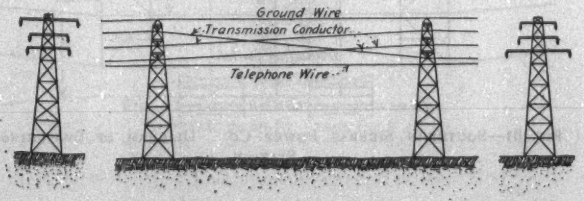


FIG. 59—WASHINGTON WATER POWER CO. TRANSPOSITION

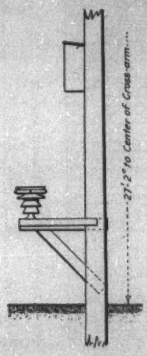


FIG. 60—WASHINGTON WATER POWER CO. DETAIL OF TELEPHONE INSULATING STAND FOR LINEMAN

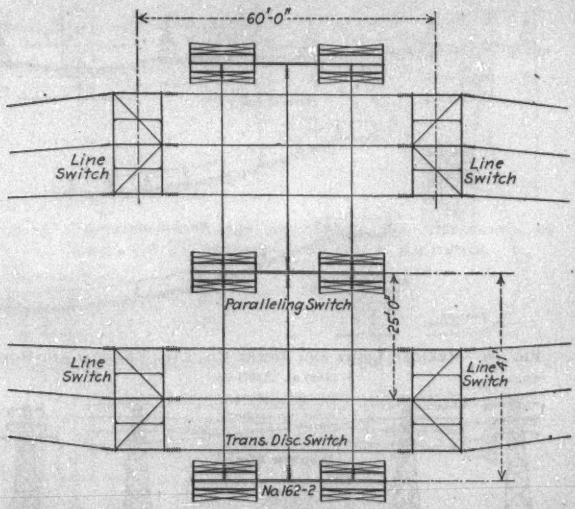


FIG. 61—SOUTHERN SIERRAS POWER CO. DIAGRAM OF SWITCHING STATION

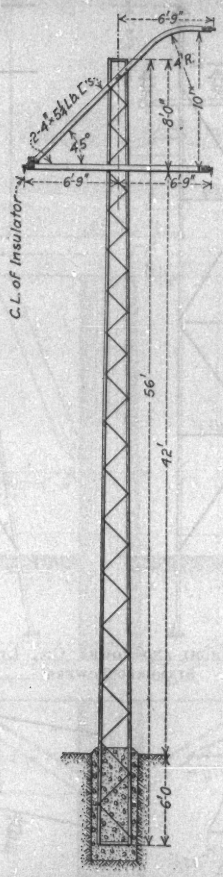


FIG. 62—SOUTHERN SIERRAS POWER CO.
DETAIL OF 56-FT. STEEL POLE

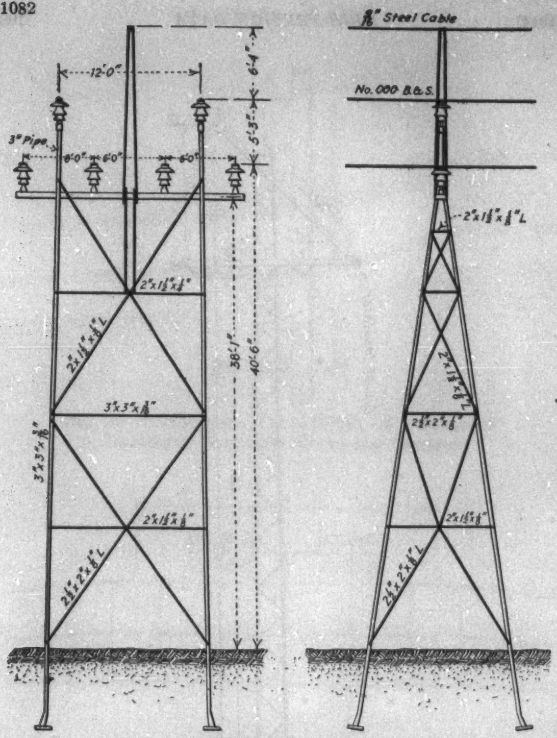


FIG. 63—MEXICAN LIGHT AND POWER CO., LTD. CONSTRUCTION OF STANDARD TOWERS

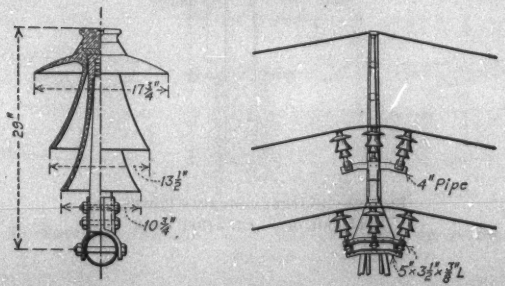


FIG. 64—MEXICAN LIGHT AND POWER CO. TOP OF SPECIAL TOWER AND SECTION OF 85,000-VOLT INSULATOR

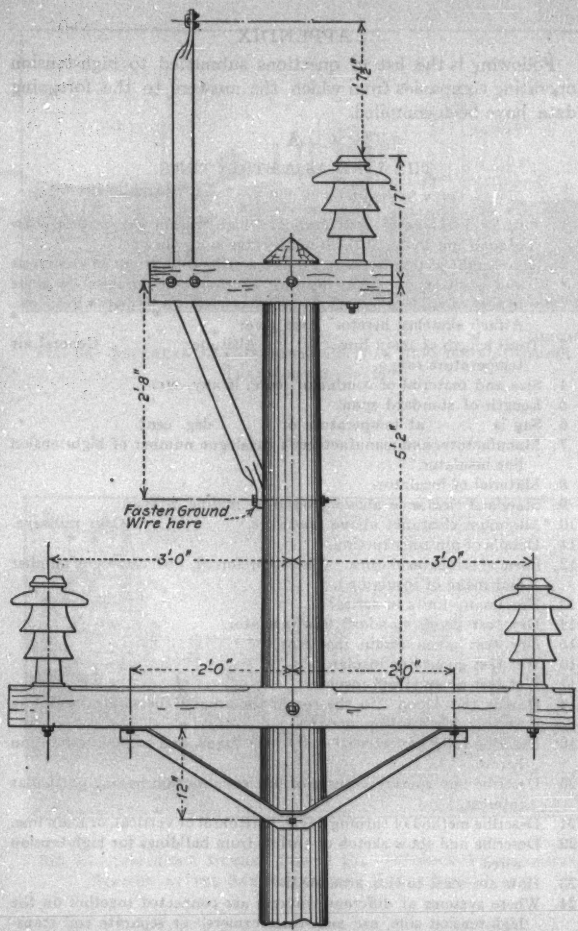


FIG. 65—"X." DETAIL OF POLE TOP—50,000-VOLT SINGLE-CIRCUIT TRANSMISSION LINE

APPENDIX

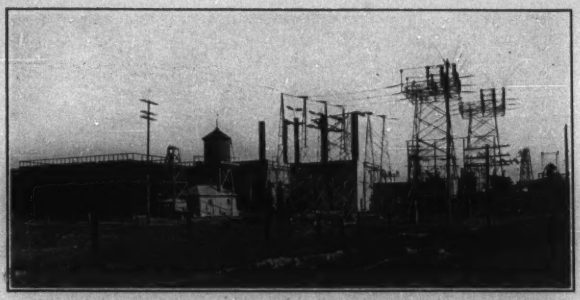
Following is the list of questions submitted to high-tension operating companies from which the answers to the foregoing data have been compiled.

A

THE LINE AS A STRUCTURE.

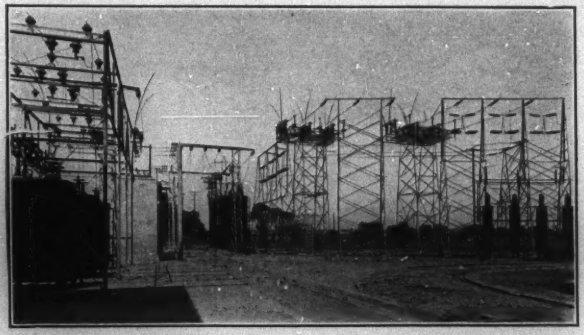
Only Systems of 25,000 Volts or Higher

1. Outline drawings of your standard high-tension lines. Side view of span and a view at the tower looking along the line.
2. Give height of pole or tower, dimensions and locations of crossarms and position of wires, distance between two circuits on same towers, foundations, show all overhead grounded wires, etc. Attach sketches hereto. Also give:
3. Total length of main line. Altitude. General air temperature range.
4. Size and material of conductor, core, if any, etc.
5. Length of standard span.
6. Sag is at temperature of deg. cent.
7. Manufacturer and manufacturer's catalogue number of high-tension line insulator.
8. Material of insulator.
9. Standard clearance above ground at middle of span.
10. Minimum clearance above roadways. Over railways.
11. Details of pin construction.
12. Form of strain insulators. (Sketch preferred, with catalogue number and make of insulator.)
13. How many units in series?
14. Dry test given standard line insulator.
15. Dry test given strain insulator.
16. Wet test given line insulator.
17. Wet test given strain insulator.
18. How is the "loop" in the conductor around the strain insulators at an anchor tower made?
19. Describe fully any exceptionally long spans, and attach description hereto.
20. Describe any special features of line construction having particular interest.
21. Describe method of turning angle, horizontal or vertical, or main line.
22. Describe and show sketch of outlets from buildings for high-tension wires.
23. How are steel towers grounded?
24. Where systems at different voltages are connected together on the high-tension side, are auto-transformers, or separate coil transformers, used?
25. What sorts of deterioration do you observe in the conductor, insulators or towers after long service?



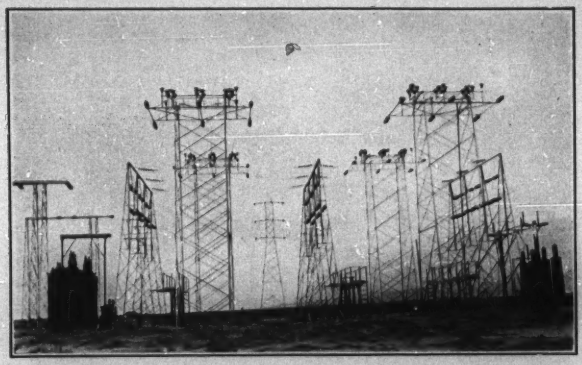
[THOMAS]

FIG. 66—SOUTHERN SIERRAS POWER CO. SAN BERNARDINO OUTDOOR TRANSFORMER STATION



[THOMAS]

FIG. 67—SOUTHERN SIERRAS POWER CO. OUTDOOR TRANSFORMER STATION AT THE SAN BERNARDINO GENERATING PLANT

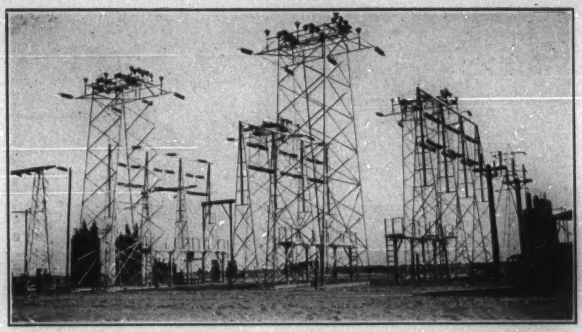


[THOMAS]

FIG. 68—SOUTHERN SIERRAS POWER CO. LONE PINE SUBSTATION—60,000-VOLT NON-AUTOMATIC CIRCUIT BREAKERS.

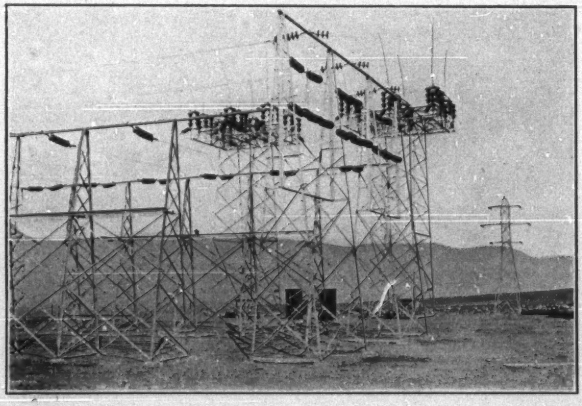
[THOMAS]

FIG. 69—SOUTHERN SIERRAS POWER CO. LONE PINE SUBSTATION



[THOMAS]

FIG. 70—SOUTHERN SIERRAS POWER CO. VIEW OF SUBSTATION AT LONE PINE

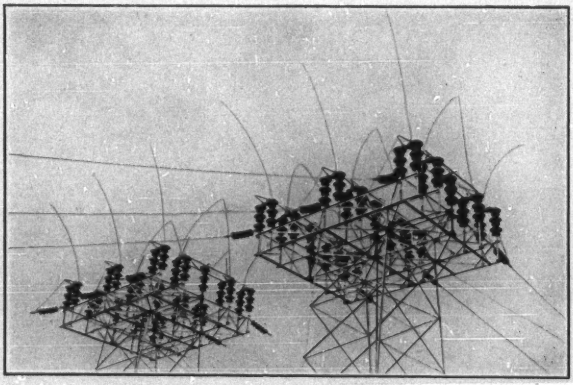


[THOMAS]

FIG. 71—SOUTHERN SIERRAS POWER CO. CONTROL STATION NEAR MOUTH OF BISHOP CREEK CANYON—COMMENCEMENT OF TRANSMISSION TO SAN BERNARDINO

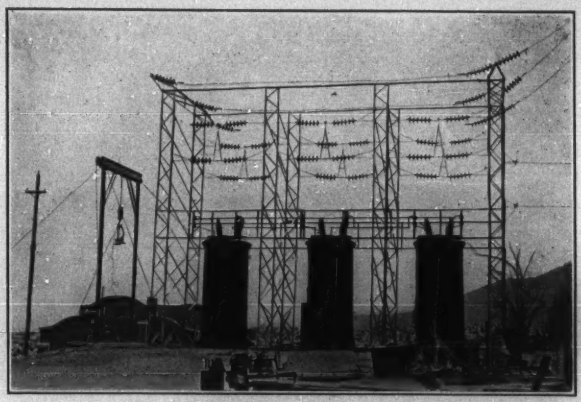
[THOMAS]

FIG. 72—PENNSYLVANIA WATER AND POWER CO. NICHOLSON'S LIGHTNING ARRESTERS



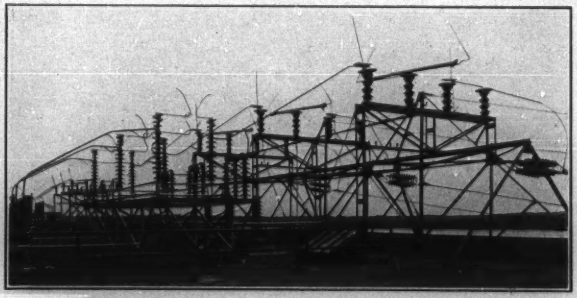
[THOMAS]

FIG. 73—SOUTHERN SIERRAS POWER CO. CONTROL STATION AT BISHOP, SHOWING DOUBLE BREAK, PNEUMATICALLY-OPERATED, SYNCHRONIZING CIRCUIT BREAKERS



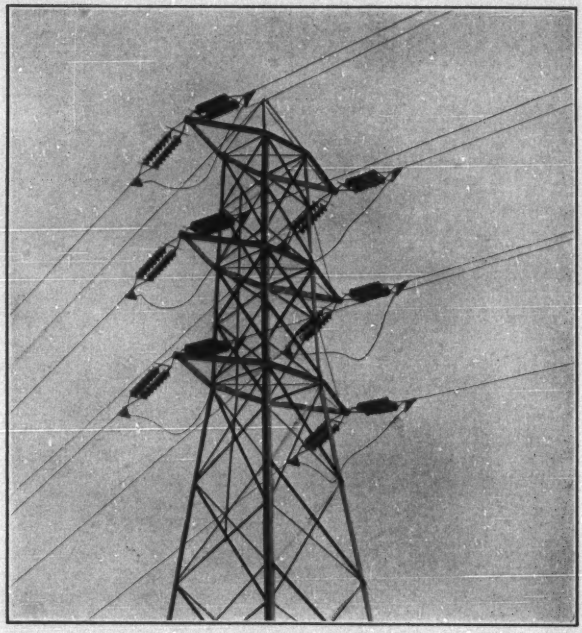
[THOMAS]

FIG 74—SOUTHERN SIERRAS POWER CO. TRANSFORMER STATION, POWER PLANT NO. 6



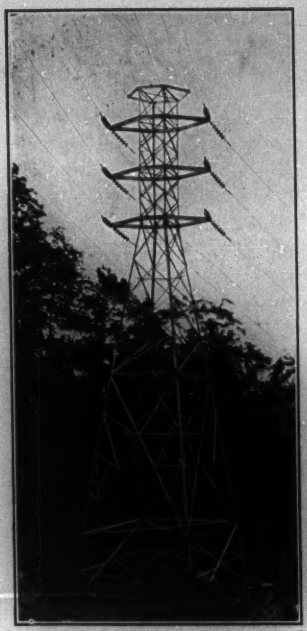
[THOMAS]

FIG. 75—MISSISSIPPI RIVER POWER CO. ROOF STRUCTURES FOR 110,000-VOLT LINE ENTRANCE



[THOMAS]

FIG. 76—MISSISSIPPI RIVER POWER CO. TURN IN LINE AT TOWER NO. 12



[THOMAS]

FIG. 77—PENNSYLVANIA WATER AND POWER CO. STANDARD ANGLE TOWER

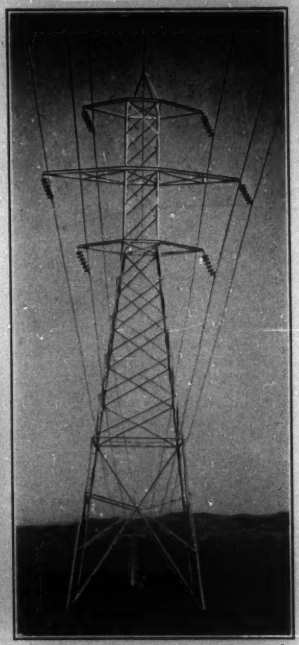


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FIG. 78—SOUTHERN SIERRAS POWER CO. TRANSMISSION LINE UNDER WIND STRESS
(See deflection of insulators.)

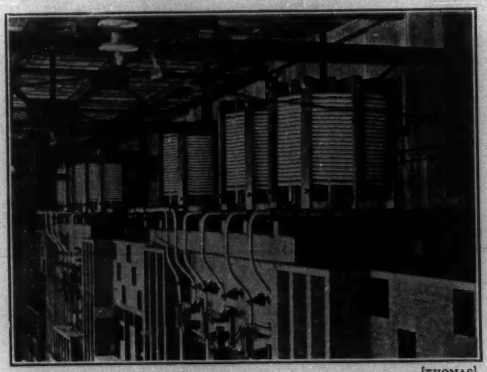

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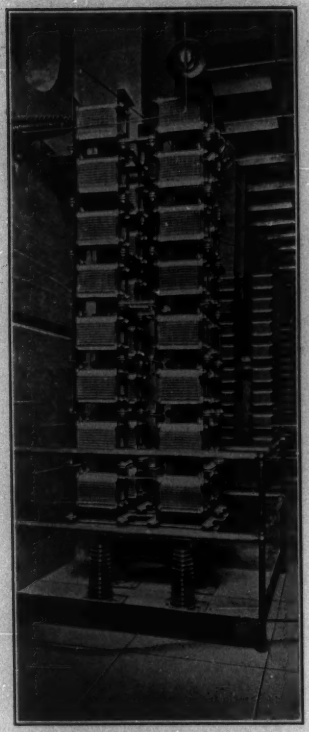
FIG. 79—PENNSYLVANIA WATER AND POWER CO. PART OF INTERIOR OF SWITCH ROOM, GENERATOR STATION, SHOWING REACTANCES



[THOMAS]

FIG. 80—PENNSYLVANIA WATER AND POWER CO.
70,000-VOLT BUS ROOM, HOLTWOOD
RESISTANCES IN NEUTRAL GROUND CONNECTION

B

CALCULATION OF LINE

Conditions on which the Original Design of the Line was Based

1. Size of conductors and elastic limit and modulus of elasticity assumed in the design .
2. Elastic limit and modulus by actual test.
3. Same for overhead grounded wires if used. Design value . Test value .
4. Breaking strength assumed in the design . Breaking strength by test .
5. Maximum strength pin, assumed in the design . As determined by test .
6. What maximum stress conditions were specified in the design for poles or towers, to determine their strength, e.g., was it made a condition that the line should stand, if all conductors were cut on one side of tower?
7. Maximum wind stress assumed for bare wire, pounds per square foot of projected area.
8. Accompanying air temperature assumed for question 7.
9. Maximum and minimum air temperatures assumed for determining limits of sag.
10. Maximum thickness ice assumed on conductor.
11. Accompanying air temperature assumed for question 10.
12. Accompanying wind pressure assumed for question 10, pounds per square foot of projected area.
13. Are special "strain" or "dead-end" towers used on tangents?
14. If so, where, and how often?
15. What stress conditions are these special towers designed to stand?
16. Have you any towers made flexible in the direction of the line?
17. If so, where are they placed, and how often have you dead-end towers?
18. What stresses are the flexible towers designed to stand, longitudinal and transverse?
19. If the outline of such flexible towers is not given under "Line Structure," please give sketch here.
20. Where suspension type insulators are used, what maximum angular deflection from the vertical under transverse wind strains was assumed in the design?
21. What was actually found (a) Steady wind conditions?
    (b) Swings?
22. What factors of safety were used in the design?
    a. Conductor, compare elastic limit with load .
    b. Tower structure .
    c. Overturning foundations .
    d. Overhead grounded wires .
23. Is the overhead grounded wire relied upon as part of the mechanical supporting structure in the direction of the line?

C

OPERATION

1. What is the standard method of cutting off high-tension lines, both for light and loaded lines?
2. How do you cut off a main line short circuit that holds on?
3. Do you use automatic overload circuit breakers? If so, where?
4. Are they instantaneous, inverse time limit or definite time limit?
5. What settings do you use on overload breakers and on time limit relays?
6. Do you use several relays with different time limits on different parts of a circuit and if so do the short time relays protect the others?
7. Do you use reverse energy relays? If so, what type?
8. When do they operate selectively? When non-selectively?
9. Can you clear a heavy main line short circuit without a synchronous load dropping out of step? If so, how, and under what conditions?
10. Do you operate any lines parallel at both ends? In this case can you cut out trouble on one line automatically without losing the load?
11. How do you locate line troubles?
12. Do you operate all lines from one busbar?
13. If so, is it a high-tension or low-tension busbar?
14. In case of several stations, are all connected directly to the same network?
15. How many power houses are connected to one system?
16. How many of these are water power?
17. How many are steam?
18. What are the capacities of each?
19. What is the maximum total load in system?
20. How do you regulate distribution of power between power stations?
21. How regulate voltage?
22. How do you secure constant voltage at intermediate points on a long line?
23. Where several power houses are connected to the same system, what happens when a short circuit occurs near one power house, that is, how does it affect the rest of the system?
24. Is the high-tension neutral gounded? If so, at how many points?
25. If so, is it through resistance?
26. Answer for each point of grounding.
27. If so, how much resistance?
28. How made up?
29. Have you ever operated, for even a brief period of time, with the line wire grounded?
30. If so, how long?
31. What was the effect on the rest of the system?
32. Have you a circuit breaker relay in connection with a grounded neutral to cut out automatically a single grounded line wire? If so, how arranged?
33. What is the total normal charging current of the system?
34. What is the power factor of the load at the generating station?

35. Do you use the method of operation which consists in dividing the plant into self-supporting groups and connecting the groups at some point to facilitate the carrying of peak loads and putting instantaneous overload breakers in these connections so that when trouble occurs in one section the others will be immediately cut off by these breakers and left to operate alone?
36. What are most common causes of interruption of service? If possible give the percentage of total interruptions caused by various kinds of trouble.
37. Have you any lead-covered cables operating at 20,000 volts or higher? If so, what sort? What success?
38. Are any such cables in series with overhead lines? If so, what protection is used?
39. What is the difference in voltage between the two ends of the line at full load? Specify the load and power factor at one end of the line and the length of the line.
40. How and where are the operations of the system controlled?
41. Do you have automatic voltage regulators on any of your generators?
42. If so, what kind? What results?
43. Have your oil switches ever failed to open a heavy load or short circuit?
44. If so, under what conditions? What type of switch?
45. Do you work on one line on a tower with another line alive?
46. As a matter of experience do your line insulators fail *on laboratory test* by flash-over, or by puncture?
47. As a matter of experience do your line insulators fail *in service* by flash-over, or by puncture?
48. Where suspension insulators puncture, which insulator in the string is the most likely to puncture?
49. Do the strain insulators fail more often than the vertical suspension strings?
50. Do you use synchronous apparatus to correct power factor? If so, how? With what success?
51. Do you use reactance coils for this purpose?
52. Have you had any trouble from mechanical oscillations or waves or swinging of your transmission conductor? If so, please explain.
53. At what frequency or frequencies do you operate?

NOTE. If the above questions are not suited to bring out the methods of operation or points of interest of your plant, please give such additional information as you may desire.

D

LIGHTNING AND LIGHTNING PROTECTION

1. What type and make of high-tension arresters do you use?
2. Where located in line? That is, whether indoors, outdoors, at exit from building, out on line, at what substations, etc.
3. Total number on lines
4. For what discharge voltage are they set, that is, at what margin over line voltage?
5. How often are they charged, if electrolytic arresters are used?

6. Is charging resistance used? Does this do away with high-frequency effect at time of charging?
7. How many lightning storms in average season?
8. How often do arresters discharge?
9. Do they discharge whenever one leg of the line is grounded?
10. How long will they stand a continuous discharge safely, as when there is a permanent ground on a line wire?
11. How many interruptions of service on main line per season due to lightning?
12. How many cases of high-tension station apparatus injured by lightning per season?
13. How many line insulators *punctured* by lightning per season?
14. How many line insulators *cracked* by arc over surface per season?
15. Are resistances used in ground connections of lightning arresters?
16. If so, how much?
17. Of what material and how made?

NOTE. If you have had any experience with overhead grounded guard wires on your transmission line, please summarize your evidence as to their effectiveness and give as a separate statement your views as to the desirability and effectiveness of such protection.

E

SPECIAL PROTECTION FEATURES

1. Do you use arc "suppressors?"
2. Do you use automatic grounding devices?
3. Do you use automatic line short-circuiting devices?
4. If you use any of the above, please give a brief outline of their principle of operation and your experience with them as fully as you may be willing to do so.
5. Do you use any other special forms of protective apparatus against short circuits, interruptions, or grounds, such, for example, as static cable protectors?
6. Do you use reactance coils in your circuits to prevent too heavy short-circuit currents?
7. If so, where are they located, in the system?
8. What maximum current do they permit on full voltage?
9. What could be the maximum short-circuit current of the system at the same point without these reactances coils?
10. Have you had any objectional features of such reactance coils develop?
11. Do you lower the generator field strength in case of trouble, either by hand or automatically?

F

TELEPHONE

1. How does your company telephone line run on the transmission poles or towers?
2. If not, how is it run and by what route with regard to the main line?

3. What size and material are the conductors?
4. How far spaced from transmission line, how are the telephone lines themselves spaced?
5. How transposed?
6. How is power line transposed?
7. What precautions are taken to protect users of the company phones?
8. Is the phone usable at all times during operation?
9. If not, when is it not usable?
10. What is the effect upon the telephone line of various sorts of trouble on the transmission line?

G

PRESERVATION OF WOOD

1. Do you use any treated wood?
2. If poles, how do you treat them?
3. If crossarms, how do you treat them?
4. If pins, how do you treat them?
5. How have they lasted? What length of time and under what general conditions?
6. How much does it cost to treat?
7. What disadvantages has treating?
8. For what conditions do you advocate wood, the use of wooden poles or crossarms?
9. Have you any special means of protecting pole butts from decay or fire?

H

MISCELLANEOUS

1. Have you outdoor substations?
2. Have you outdoor transformers?
3. Have you outdoor switches?
4. If either, please state essential features briefly and whether you are pleased with them.
5. Do you use "breathers" to keep moisture from tanks of outdoor type of apparatus? What sort and what success?
6. Does moisture actually penetrate your weatherproof tanks?
7. How do the high-tension terminals act in wet weather?
8. How do you protect tanks from the heat of the sun?
9. Have you tested oil from outdoor apparatus that has been over a year in service? If so, what result?
10. Do you follow the overhead crossings specifications prepared for the national standard by the Joint Committee on Overhead Line Construction of the N. E. L. A.?
11. Do you use any bimetallic or copper-clad cables?
12. If so, are they satisfactory? How used?
13. Any observations on corona?

DISCUSSION ON "ENGINEERING DATA RELATING TO HIGH-TENSION TRANSMISSION SYSTEMS" (SUB-COMMITTEE REPORT: THOMAS), DETROIT, MICH., JUNE 25, 1914.

John B. Fisken: On page 1023 it is stated for the Washington Water Power Company, "We have noted no deterioration in conductors." That, as far as I know, was true up to within the past few weeks. Since I left home I have been advised that a very serious deterioration has been noticed in some of the conductors. I have a small sample of wire here which was sent to me at Detroit, which I will give to the chairman; it shows the deterioration to which I refer. I do not know what the cause is, and I cannot account for it, unless it is a corona effect. It appears to be a very serious matter. This line has been in operation about eleven years. The first eighteen months it was operated at about 45,000 volts, and since then at 60,000 volts. The triangle is 42 inches. The insulators are carried on iron pins and wooden poles, and until about two years ago the pins were not grounded. At that time we did ground the pins and that has had some effect on the wire, possibly. I merely call your attention to this to show that we at any rate have found deterioration in the conductors.

Percy H. Thomas: There is a marked deterioration in the wire; a wasting away in spots of the metal at least 1/16 in. deep. We are greatly indebted to Mr. Fisken for bringing this point forward, and it is a matter that we should all bear closely in mind. What part of the system was this taken from, and what were the conditions surrounding the line at that point?

John B. Fisken: The climate is such that for about two months in the summer there is practically no rain. The average annual precipitation is about 22 in., and the elevation where that wire was taken down was about 2500 ft.

Percy H. Thomas: Was this deterioration noticed generally over the system, or at some particular location?

John B. Fisken: We have only gone over a few miles of the line, and it has been noticed all over that portion. This matter has only come up within the last month, so we have not had time to make a full examination of the rest of the line, which is about 100 miles long.

S. C. Lindsay: The Committee states that there were only a few companies using protective relays, and that the Puget Sound Traction, Light and Power Company does not state the result of selective action. When the data were compiled we had only two lines equipped with reverse-power relays, and we had not had a case of trouble on either line since they were installed. The question of equipping our whole system with automatic relays had been thoroughly investigated, and the equipment was being installed when these data were supplied. Since forwarding these data to the committee we have had

several cases of trouble, and on the whole are getting very encouraging results from our automatic relays on networks of lines. We have three networks, 50,000-, 13,000- and 2200-volt lines. Our relay installation is not complete at this time, but within the course of a year our company will be able to contribute additional data on the question of automatic relays for protecting networks.

Percy H. Thomas: The matter of protecting telephone lines on the same towers as high-tension lines, or even in the same general neighborhood and paralleling high-tension lines, is a most important one. There are two difficulties encountered, the difficulty of talking and hearing, and the danger to the operator.

The difficulty of talking is due to electrostatic, and, to some extent, electromagnetic, induction between the high-tension line and the telephone line. It is of course the long parallelism between them that makes the situation serious, on account of the very great sensitiveness of the telephone. The telephone line is so sensitive to this disturbance that putting the telephone line a mile away from the power line will not prevent interruption of telephone service under most conditions whenever the power line is grounded or short-circuited, or by the charging of electrolytic arresters, or almost any kind of electrical disturbance.

If the telephone line is a mile away and has not protective means, talking is usually impracticable when the power line is upset from any cause. It is relatively easy, however, to protect such a telephone line so that talking is good, for example by the use of drainage coils. The drainage coil is a transformer winding connected between the two telephone wires and having its middle point grounded.

The characteristic of the voltage disturbance produced in a telephone line by the power line, which distinguishes it from the useful voltage in the telephone line producing the talk, is the fact that induction from the power line affects both telephone wires alike. If the induction is such as to raise the potential of the telephone wires they are both raised at once, and if it is such as to lower the potential they are both lowered at once. Talking through telephone wires, on the other hand, produces potentials positive on one telephone line and negative on the other. The power disturbance raises them or lowers them together. A device which will prevent a change of potential of the same sign in the two wires, but will permit potentials of opposite signs to exist in the two wires, gives the desired result of permitting talk and resisting induction. The drainage coil does just this. The induced currents which tend to flow to ground at the same time from the two telephone wires are unimpeded, since the magnetic effects in the windings will neutralize each other, and will not produce any magnetism in the core of the transformer. Therefore, the only impedance to ground they meet is due to the resistance of these windings and to whatever magnetic leakage there may be between the two halves of the winding.

Obviously, the disturbance produced in the telephone wires by the power line is of such a nature as to send a charging current into, or out of, the two telephone wires at the same time. If no charging current can flow, the induction affects the potential of the two wires. With a connection to ground, the effect of the disturbance is to produce charging current in the two wires.

It is impossible to eliminate absolutely the resistance offered by the drainage coil to the charging current to ground, but the residual 50 or 100 volts, of course, is immaterial. The one precaution to observe with this kind of protection is to make sure that there is no condition in which the power line disturbance can produce so large a charging current to the telephone wires through the drainage coils as to burn them out.

Where the exposure of a telephone line to a high-tension line is a good many miles, it is good practise to have a number of these drainage coils, so if anything happens to one, others will remain, and protection at any one point does not depend on a coil a hundred miles away.

So much for the first type of disturbance of the telephone line, and drainage coils, properly installed, are pretty nearly sufficient for protection.

The second type of disturbance is the danger to operators. The 1 to 1 transformer is certainly a very great protection, but remember this—they are generally tested at not over 25,000 volts, which is hardly sufficient, on a 100,000-volt system, to give absolute protection. It is desirable to have spark gaps and fuses as well.

The insulating transformer very materially cuts down the transmission of speech. It is not possible to speak as clearly through the insulating transformer as if the transformer were not there.

Ernest V. Pannell: In view of the very valuable data given in this report, it is scarcely fair to criticise its lack of completeness, but I think it would have been more interesting if it had been possible for the report to show how the design of the line is influenced by the conducting material used. In going through this list of transmission lines, it is notable that 40 per cent of them are using aluminum conductors to a greater or less extent. In addition we see a metal in use which I believe is copper-clad steel, and also steel-core copper and steel-core aluminum. Now if we had a thorough and exhaustive report, comparing these various materials side by side, with their advantages and disadvantages, and the various experiences in operating them, it would, I am sure, fill a very wide gap in our practical knowledge of transmission line design at the present day.

With particular reference to long spans, of course this is the incentive which has brought most of these high-tenacity materials into use, and in this connection it has frequently been said that aluminum is good for spans which do not exceed six or seven hundred feet. In view of the remarks of the Pacific Gas and Electric Company in this report, however, and of other

companies operating with aluminum on their long spans, this seems no longer to hold good; and with the greater tenacity obtained in the present-day product, it would seem that aluminum is perfectly satisfactory on all spans which can be run with copper. An additional piece of information comes to my mind, and that is a transmission line recently erected in Norway, where they are putting on spans up to 2300 ft. in length, which are being made with cables of a light aluminum alloy having a tenacity of 36,000 lb. per sq. in.

Where a line has been designed for aluminum conductors as an alternative to copper, it does not seem to me that the correct principle is always followed. Almost invariably the aluminum conductors are chosen equivalent to the conductivity of the copper only. Necessarily, the aluminum will have a greater sag, and higher and more costly towers will be required. If, as an alternative, cables of larger area of cross-section were used, the tension on the lines could be increased, the sag decreased, and the towers, although they would have to be stiffer, need not be as high, and I believe the line would be more reliable throughout and at least as cheap.

If there is any information forthcoming on this matter of compound steel-copper and steel-aluminum conductors, it would be interesting to know just how the stresses are distributed in them. I take it, that where a steel-core is employed, instead of aluminum or copper, the lay of the steel is longer than that of the outer metal, so that it takes the major part of the pull.

The sample which Mr. Fisken showed to us was very interesting, and it appeared as if the trouble was due to abrasion rather than corrosion. I do not know whether anyone will bear me out in that. I will ask Mr. Fisken, in view of the fact that I believe he has some aluminum wire on his system, whether the aluminum conductors have shown similar trouble, or how they are behaving. It is a notable fact that under many atmospheric conditions which cause copper to deteriorate, aluminum has been found to operate satisfactorily.

Percy H. Thomas: What do you mean by a tenacity of 36,000 lb. per sq. in.? Is that the ultimate strength of the elastic limit?

Ernest V. Pannell: That is the ultimate strength per sq. inch.

John B. Fisken: We took down about 50 miles of aluminum wire that had been in operation for about five years and nothing of this kind was found; whether it will be in the same condition after ten years, or not, I cannot tell.

Percy H. Thomas: Possibly some of you gentleman do not happen to have noticed that we have at least two or three long transmission lines which are using a special cable with a steel center, and a number of aluminum strands wound around it, the steel being very high strength steel, and the aluminum giving conductivity and giving large diameter to keep down corona.

I wonder if there is anyone present who can give us any further information about that steel-aluminum cable.

E. E. F. Creighton: I wish to say a few words about the vacuum lightning arrester which has been under development for a number of years, to have no misunderstanding of the limitations of its use. Mr. Emerson P. Peck has taken the initiative in applying this arrester to the protection of telephone wires situated on 11,000-, 22,000- and 110,000-volt lines of the Georgia Railway and Power Company. The lightning arrester was developed specifically for signal circuits of steam railways and it was intended in these circuits to make the arrester so that it would never short-circuit. A short-circuited arrester on a signal circuit means a false signal of safety, and therefore is very dangerous. This arrester was developed with that idea in mind, to avoid the danger of short-circuiting. As a result, the arrester will stand momentarily 1000 amperes of direct current at 600 volts, while a circuit breaker opens, without having its electrodes welded together—in fact, it will do this a number of times. Opening up an arrester after tests of that kind we found the electrode very much shrunken in size, but in no case was the electrode melted in such a way as to come in contact with the outer copper tube. I am not bringing this matter up at this time to describe the arrester, but to describe the limitation, and therefore I shall pass immediately to the point in mind.

While the arrester was developed to withstand heavy current for a brief time, it was not given sufficient cooling area to discharge a small current for a long time. It frequently happens that an accidental arcing ground occurring on a system lasts for a considerable length of time before it is removed. If this arrester is so placed that discharges pass through it during this period it is liable to be overheated and damaged. Mr. Peck has apparently found no trouble from this source, and it is probably due to the fact that continuous discharges do not take place for a long time through the arrester in the position in which it was used. An arrester having plenty of cooling surface can be made for this particular service and a few of them have been put out. I think the important point is that with the arrangement that Mr. Peck has used* it seems unnecessary to take the precaution of using a larger lightning arrester and a more expensive one in order to keep it cool.

In the matter of the damage done to the wire which Mr. Fisken showed, we have had in certain types of apparatus which we have built in the laboratory something quite similar that makes us think it is the same thing. An electrostatic relay in which an insulator was used to furnish the electrostatic pull produced just such corona, which formed nitrous oxide, and with the natural moisture in the air, formed nitric acid. This corona discharge, which was a little heavier than the blue discharge which gives ozone, was confined in a glass box. The nitrous oxide continued

*Pages 1042-1046, this volume.

to increase in density, and as a result every one of the metal parts inside, except the aluminum, was very badly corroded. It would seem that this is the same thing that Mr. Fisken found, in that the wire is eaten out directly above the insulator where it lay on top of the porcelain, in the location where the corona would be the strongest. Taking into account the high altitude and the fact that the insulators were made many years ago, it would lead one to believe that the static charging current in that insulator might be sufficient to get the corona above the value which causes ozone, into that region of discharge where nitrous oxide is formed. One can easily determine visually the intensity of corona discharge which forms nitrous oxide. It is marked by the appearance of definite little threads or bright streamers in the otherwise uniform blue brush discharge.

Percy H. Thomas: What Professor Creighton says certainly sounds very reasonable, and I want to ask Mr. Fisken if any of the insulators in this neighborhood are on wooden pins.

John B. Fisken: All iron pins.

Percy H. Thomas: Have you examined the tops of any of the pins—do they show any sign of deterioration?

John B. Fisken: No.

Percy H. Thomas: I should say the iron would be attacked by nitrous oxide if it existed.

John B. Fisken: We have taken off a number of pins and never noticed anything of that kind.

Percy H. Thomas: Are they set in cement?

John B. Fisken: No, in lead.

Percy H. Thomas: The digestion of tops of wooden pins suggests this same sort of action.

F. W. Peek, Jr.: The explanation of the brush discharge as the cause of the deterioration of the line conductor, which Mr. Fisken has shown, is undoubtedly the correct one. This occurs at or near the insulator. Where the wire is tied to the insulator there is the metal conductor, a thin film of air, a thickness of porcelain, and the pin. There is thus a condenser with the line conductor as one plate, air and porcelain in series as the dielectric, and the metal pin as the other plate. The voltage across this condenser is equal to line voltage divided by $\sqrt{3}$. The same dielectric flux passes through the porcelain to the air. The permittivity of air is 1 and of porcelain is 5. The porcelain "conducts" the dielectric flux five times as well as air. The voltage gradient in the the air film is thus five times what it is in certain parts of the porcelain. This air film breaks down as a brush. Air consists of a mechanical mixture of oxygen and nitrogen. The oxygen is O_2 $(O=O)$ and is inactive. In the brush it splits up as O. Recombination takes place as O_2 and O_3 $\left(\text{ozone, } \begin{array}{c} O \\ \wedge \\ O\text{–}O \end{array}\right)$. Both O and O_3 are chemically active and oxidize the conductors. At high gradients on the air, nitrogen

also combines with the oxygen and in the presence of moisture forms nitric acid. This also attacks the conductor. Each insulator is a small ozone and nitric acid generator. It can be prevented by a properly placed corona shield.

Aluminum is affected to a much less extent by the above cause. Either aluminum or copper may, however, deteriorate very rapidly due to desulphurizing, and other mining processes.

Percy H. Thomas: I want to call attention to the fact that it is not excessive line potential, primarily, that breaks down the small air gap between the insulator and the conductor, it is the *fall of potential* across the air gap itself. With a small enough air gap, a low potential will produce this breakdown. Mr. Peek has spoken of a similar action in the windings at the end of the coils of the armature of a 200- or 300-volt generator, where a concentration of potential may under some circumstances be sufficient to produce this acetic or nitric acid formation, and deteriorate the insulation. The same thing occurs in rubber-covered underground cables where there is a great concentration of potential, and when the ends of the rubber covering are exposed to the air there is oftentimes a hardening or deterioration of the rubber due to oxidation from the formation of ozone. Those of you who use suspension insulators may feel secure in this matter with the idea that the insulators are connected to the conductor by a metal clamp, and no difference of potential can occur to form nitric acid on the conductor in the clamp.

R. Fleming: Regarding the action of nitric acid under atmospheric conditions, I do not remember having seen it proved very conclusively just what action takes place. It seems to me we have here an opportunity to get at least tentative proof as to what action takes place. It is surely chemical. On examining the sample of wire you will find there is plenty of deposit which would enable a chemist to analyze and determine its chemical nature. It is probably sulphate, it may be nitrate, or it may be carbonate of copper. The electric discharge alone would probably not disintegrate wire in the manner here shown.

H. H. Norton: I would suggest that a number of samples be collected and submitted for analysis to some chemist capable of performing such an analysis. It would require considerable work to do it. I ask Mr. Fisken if there are any smelters in the vicinity. Smelter fumes are likely to produce sulphates.

M. von Recklinghausen: I have examined this piece of wire, and to me as a chemist it looks strange that it is attacked deeply on two points. These are probably the points where the tie wire has touched this wire. There may be two explanations here—one is mechanical, but I do not think that is likely. The other may be electrolysis. The tie wire is not of the same metal, although both are supposed to be pure copper. Both are not pure copper. They are different in composition, and it is possible that there is some electrolytic action going on between the two and the humidity from the atmosphere. I offer that

merely as a possible explanation. I cannot say, offhand, that that is the cause, but it looks to me very much as if such electrolytic action between the tie wire and the conductor itself could take place due to the humidity as an electrolyte..

F. W. Peek, Jr.: I want to answer the question which has been raised, and state that such an analysis has been made, though not on Mr. Fisken's cable. We have made analyses on other samples, and found a combination of nitrogen and copper.

D. D. Ewing: In looking over the samples of wire brought by Mr. Fisken, I noticed that the deposit of salt was heavier on the pole insulator wire than on the two arm insulator wires. It seems to me that this indicates that the corrosion is worse on the pole wire than on the arm wires. If such is the case, it does not look to me reasonable that it is a nitrogen proposition altogether.

I believe Mr. Fisken made the statement that for two months in the year there was no rainfall in the district traversed by this line. He did not say anything about the soil and dust conditions, but I would judge, if there is no rain for two months in the year, that it gets pretty dusty. If the soil contains either soluble organic acids, or inorganic salts, dust in combination with water might produce the corrosion. The salt looked to me like carbonate or sulphate, or possibly nitrate, although it is impossible to determine its exact nature by inspection.

R. E. Argersinger: I want to call attention to the report of the Pennsylvania Water and Power Company engineers on the operation of their system, particularly as regards the use of reverse power relays at the substation end of the line and inverse time limit relays at the generating station, and also to point out that they are doing automatic switching on the low-tension side of the transformers at both ends of the line. This matter is referred to on pages 1026 and 1027 of the report. This system includes a 70,000-volt line, about 40 miles long, two circuits in parallel on the same tower line, with neutral grounded through resistance. As the report points out, it is difficult to get a clear idea of the relay action, since the operation is complicated by the use of arc extinguishers and also field-destroying devices. The relays are set with a time limit so that the arc extinguisher will operate first in case of flash-over to ground, and if that fails to relieve the trouble the relays operate the switches only on the line affected, and the point is that they actually cut out the circuit in trouble without disturbing the parallel circuit and without interruption of service. It is interesting to note that a few other companies are introducing this system of operation. Mr. Lindsay says his company is going into it, but that they have not had much experience yet. In my opinion, this is one of the most important features to be considered in the layout of a high-tension transmission system.

In an article I wrote, published in the *G. E. Review* for June, 1913, this system of connections was described. In an elemen-

tary way such a system might be represented by the diagram in Fig. 1, herewith, which represents a generating station connected to a substation by two transmission lines.

The normal condition of operation would be to have all of the generators in parallel on the bus A and all of the feeders in parallel on the bus D. The high-tension buses B and C would normally be opened by S and T. Switches E and G would be equipped with inverse time limit relays. Switches K, P, R and M would be non-automatic, and switches F and L would be equipped with reverse power relays. In case of trouble, then, on one line, say at X, the switch F would be opened by the reverse power relay. Switch E would be opened by the overload relay. The load would be automatically thrown over to the other line without interruption of service. This means that for a short time the second line and its transformers would possibly be overloaded, but in the worst case such an overload would not exceed 100 per cent and the apparatus should be capable of carrying such an overload for a period of time sufficient to open switches K and M and close switches S and T, after which transformer banks H and I can again be put into service in parallel with V and W on the second line.

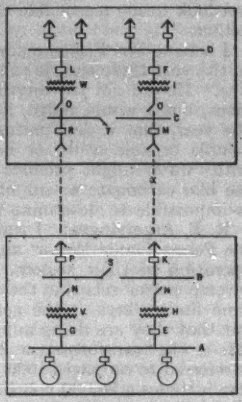


FIG. 1

The scheme of operation would be exactly the same if each of the four transformer banks shown were replaced by two or more banks, so long as they were paralleled on one high-tension line, under which conditions, in order to clear the line, it would be necessary to cut off all of the low-tension transformer switches involved. Usually it is not practicable to carry much over 20,000 kw. on a single transmission line, and a single bank of transformers can readily be used with a line of such capacity, that is, each single-phase transformer would be rated at say 6666 kw. Such a size would be economical for high-voltage design and the entire layout would be cheaper, as regards both transformers and switching equipment, than if a greater number of transformer banks were used.

This system permits, under ordinary conditions, all of the automatic switching to be done on the low-tension side, which in itself is an advantage. Some tests were made about two years ago on a large 44,000-volt system by putting spark gaps across individual coils of the high-potential winding of a transformer

and setting up disturbances on the high-tension line. The voltages across the coils, indicated by the spark gaps, varied from something like three to four times normal in case of an arcing ground to about twenty times normal for operation of a high-tension switch. Such results merit careful consideration. Further, with the transformers grouped with relation to each line, instead of being paralleled on the high-tension bus, the effective reactance in circuit when a short circuit occurs in the high-tension line is so much higher that the rush of current is materially lessened, thus decreasing the danger of damage to line insulators by high-power arcs and of burning off line conductors. I believe that entirely aside from any question of the danger of high-tension switching, the advantages of such a system of connections merit its use simply from the standpoint of decreased first cost of transformers and switching equipment, and the reduction in destructive effects of line disturbances, due to the increased effective reactance.

In the past, some objection has been made to reverse energy relays, as it was claimed that under the potential drop due to short circuit they would fail to operate properly. This difficulty has been practically done away with in most of the reverse energy relays now on the market, and further, under the conditions which usually obtain, they will not operate on overloads. Only recently, in putting into service a 120,000-volt system, about 150 miles long, where the principles indicated above were carried out strictly, a short circuit was made on the high-tension side of one of the substation transformers. The reverse energy relay acted promptly, notwithstanding the drop produced by the short circuit. Several other occurrences took place causing line disturbances, such as a lightning stroke on the line close to the generating station, a short circuit produced by wire falling across transmission line, etc., but in each case the relays operated properly so as to cut out only the line in trouble, without interrupting service. The diagram, Fig. 1, shows only two simple stations. The same principles, however, can be applied to any number of stations and substations tied together in a system, provided there are two transmission circuits.

E. A. Lof: There is one point of particular interest in this report, and this is the section on pages 1029 and 1030 dealing with the operation of a system with one of the phase wires grounded. It is notable here that for systems of very high voltage the effect of such an operation has been rather severe. One company, for example, states that it has had numerous punctures of insulators and breakdowns of bushings, while another company states that the effects have been too severe to operate its system with one wire grounded.

This brings out an important point. For a Y-connected system with the neutral grounded, the grounding of one phase wire will short-circuit this particular phase and the circuit breakers will trip, thus entirely cutting out the line. For a non-

grounded, delta-connected system, however, the grounding of one phase will have the effect of increasing the capacity of the line. Under normal operation this capacity is in proportion of the voltage to the neutral, but when one line becomes grounded this voltage is increased to the full line potential, and the charging current will be proportionately increased. This in turn raises the voltage at no-load, which will be about 70 per cent higher than it would be when under normal operation. Actual experience has proved that this is the case and it probably will be one of the most important factors which will decide against delta connection for systems of very high voltage.

Selby Haar (by letter): The report which is now laid before the Institute is a thorough piece of work, and one which fully entitles the committee to the special thanks of the members. It is regrettable, however, that approximately complete replies were obtained from less than one-fourth of the companies addressed.

The writer, having recently made a somewhat similar investigation (covering transmission systems all over the world, however), would like to call attention to certain practises brought out in the report by citing other solutions of the same problems. (The numbering of the following items refers to the list of questions given in the Appendix to the committee report).

A-2. The tower is seldom used abroad, metal poles being selected for high voltages, and wood or concrete for lower voltages.

B-1 to 15. The following data apply to a 70,000-volt Swiss line recently built.

1. 19-strand cables 0.394 in. diameter, breaking strength 57,000 lb. per sq. in., E = 17,700,000 lb. per sq. in. (working stress 8500 lb. per sq. in.).
3. 7-strand cables 0.315 in. diameter, breaking strength 113,000 lb. per sq. in., E = 31,500,000 lb. per sq. in.
6. Wind pressure only, for ordinary poles.
7. 14.3 lb. per sq. ft.
8. −25 deg. cent.
9. + 40 deg. cent.; − 25 deg. cent.
10. Snow (not ice) 0.394 in. thick, weighing 10 lb. per cu. ft.
11. − 25 deg. cent.
12. 14.3 lb. per sq. ft.
13. Yes.
14. Every $\frac{3}{8}$ to 1 mi.
15. All wires on one side broken, and wind pressure of 20.4 lb. per sq. ft. adding directly to conductor pull.

B-23. This is not infrequently claimed.

C-24. In Europe, the high-tension neutral is usually not grounded, but the generator neutral is.

C-38. The transmission line of the Moutiers-Lyons direct-current system in France, the operating voltage of which has reached about 80,000 volts, includes about 2.5 miles of cable (out of 112).

D-1. Foreign operating companies use the same types of lightning arresters for all high tensions, namely, horn gaps with series resistance, reactance coils, and liquid static dischargers. Condensers are being tried in several places. There is also to be noted an attempt to proportion the whole transmission and switching system to minimize as far as possible the generation of excess voltages.

E-1. The opinion of several experienced American engineers is that an effective arc suppressor and a plain horn gap, set rather high, give protection which is "hard to beat."

For the benefit of members who have to examine certain features of transmission plants in great detail, a list of references, mostly to periodical literature, collected by the writer in his investigation (*Electrical World*, April 25, 1914, p. 925) is appended. In this list are descriptions, etc., of over fifty plants designed for 70,000 volts or above.

High-Voltage Power Transmission Systems

Pacific Light and Power Co., 150,000 volts.
Elec. Jl. 1913, p. 768.
Elec. Rev. & West. Elecn. 3-1913, p. 583.
Elec. Wld., 6-1912, p. 1200, 1342; 11-1913, p. 1108; 1-1914, p. 337, 385.
Elek. Zeit., 10-1913, p. 1242.
Eng. News, 11-1913, p. 843.
Glas. An., 6, 7, 8-1913, p. 224, 5, 24, 51.
Au Sable Electric Co., 140,000 volts.
Elec. Wld., 4-1912, p. 795, 843; 6-1912, p. 1195.
Elek. Zeit., 10-1913, p. 1242.
Eng. Mag., 4-1913, p. 53.
Glas. An., 6, 7, 8-1913, p. 224, 5, 24, 51.
Lundquist, "Transmission Line Construction," p. 46.
Southern Sierras Power Co., 140,000 volts.
El. Rev. & West. Elecn., 10-1912, p. 814.
Elec. Wld., 8-1912, p. 298; 8-1913, p. 234.
Elek. Zeit., 10-1913, p. 1242.
Glas. An., 6, 7, 8-1913, p. 224, 5, 24, 51.
Jl. Elec., Pr., Gas 7-1913, p. 1, 33.
Utah Power & Light Co., 130,000 volts.
Elec. Wld., 7-1913, p. 106.
G. E. Rev., 1913, p. 359.
Pacific Gas & Electric Co., 125,000 volts.
Elec. Wld., 11-1913, p. 1055.
Eng. Rec., 11-1913, p. 573.
West Penn. Traction & Water Power Co., 125,000 volts.
Elec. Rev., & West. Elecn. 11-1912, p. 990; 4-1913, p. 726.
Elec. Wld., 6-1912, p. 1280.
Iron Age, 11-1912, p. 1296.
Tennessee Power Co., 120,000 volts.
Elec. Rev. & West. Elecn., 2-1913, p. 267.
Elec. Wld., 4-1912, p. 820; 3-1913, p. 644,696; 5-1913, p. 1111; 10-1913, p. 868.
Power, 3-1914, p. 360.

Connecticut River Transmission Co., 120,000 volts.
Elec. Wld., 10-1913, p. 685; 3-1914, p. 565.
Inawashiro Hydroelectric Power Co., 115,000 volts.
Elec. Wld., 3-1912, p. 524; 5-1913, p. 1058.
Engg. London, 10-1913, p. 35.
Z. V. d. I., 4-1912, p. 569.
Au Sable Electric Co., 110,000 volts.
Elec. Wld., 11-1906, p. 841; 11-1907, p. 850; 2-1909, p. 354; 9-1909, p. 664; 6-1912, p. 1195.
Elek. Zeit., 10-1913, p. 1242.
Eng. Mag., 4-1913, p. 53.
Eng. Rec., 10-1907, p. 418, 462.
G. E. Rev., 1909, p. 86.
Hydroelectric Power Commission of Ontario, 110,000 volts.
Elec. Wld., 1-1912, p. 33, 96, 137; 6-1912, p. 1195.
Elecn., London, 3-1912, p. 912.
Elek. Kr. & B., 1909, p. 337; 1910, p. 526, 727.
Elek. Zeit., 10-1913, p. 1242.
Eng. Mag., 4-1913, p. 53.
G. E. Rev., 1912, p. 336; 1913, p. 352.
Glas. An., 6, 7, 8-1913, p. 224, 5, 24, 51.
TRANS., A. I. E. E., 24-1905, p. 807.
Lundquist, "Transmission Line Construction," p. 45.
Lauchhammer, A. G., 110,000 volts.
Elec. Wld., 10-1911, p. 1057; 6-1912, p. 1195.
Elek. Zeit., 1911, several places; 10-1913, p. 1242.
Lundquist, "Transmission Line Construction," p. 96, 97.
Georgia Railway & Power Co., 110,000 volts.
Elec. Rev. & West. Elecn., 2-1913, p. 267.
Elec. Wld., 5-1911, p. 1127; 6-1912, p. 1195; 12-1913, p. 1257, 1309.
Elek. Zeit., 10-1913, p. 1242.
Eng. Mag., 4-1913, p. 53.
Eng. News, 1-1914, p. 240.
G. E. Rev., 1912, p. 336; 1913, p. 352; 1914, p. 608.
Alabama Power Co., 110,000 volts.
Elec. Wld., 3-1912, p. 610; 1-1913, p. 68; 6-1913, p. 1278; 9-1913, p. 527
G. E. Rev., 1913, p. 386.
Mississippi River Power Co., 110,000 volts.
Elec. Wld., 4-1913, p. 715; 5-1913, p. 1157.
Elek. Zeit., 10-1913, p. 1231, 1242.
Eng. Mag., 4-1913, p. 53.
G. E. Rev., 1912, p. 336; 1913, p. 352; 1914, p. 85, 375.
Glas. An., 6, 7, 8-1913, p. 224, 5, 24, 51.
Lehigh Navigation Electric Co., 110,000 volts.
Elec. Wld., 4-1913, p. 902; 5-1914, p. 1035, 1093.
Cedar Rapids Manufacturing & Power Co., 110,000 volts.
Elec. Wld., 4-1913, p. 902; 7-1913, p. 105; 8-1913, p. 319.
Eng. Rec., 10-1913, p. 461.
G. E. Rev., 1913, p. 336.
Mexican Northern Power Co., 110,000 volts.
Elec. Wld., 5-1913, p. 1190; 7-1913, p. 155.

G. E. Rev., 1912, p. 336.
Ebro Irrigation & Power Co., Ltd., 110,000 volts.
Elec. Wld., 1-1913, p. 212.
Chile Exploration Co., 110,000 volts.
Elec. Wld., 5-1913, p. 1191.
Eng. & Min. Jl., 1-1914, p. 63.
Sierra & San Francisco Power Co., 104,000 volts.
Elec. Wld., 6-1912, p. 1193; 9-1908, p. 667; 10-1908, p. 946.
Elek, Kr. & B., 1910, p. 160.
Eng. Mag., 4-1913, p. 53.
Eng. News, 5-1909, p. 516.
G. E. Rev., 1912, p. 336; 1913, p. 352.
Glas. An., 6, 7, 8-1913, p. 224, 5, 24, 51.
Lundquist, "Transmission Line Construction," p. 45.
Great Falls Power Co., 102,000 volts.
Bull. A. I. M. E., 8-1913, p. 1907.
Elec. Wld., 6-1912, p. 1195.
Elek. Zeit., 10-1913, p. 1242.
Eng. Mag., 4-1913, p. 53.
G. E. Rev., 1911, p. 149, 207; 1912, p. 336; 1913, p. 352.
Glas. An., 6, 7, 8-1913, p. 224, 5, 24, 51.
Trans. A. I. E. E., 1911, p. 2002.
Yadkin River Power Co., 100,000 volts.
Elec. Wld., 3-1911, p. 748; 4-1911, p. 799; 5-1911, p. 1128; 8-1911, p. 261, 4-1912, p. 774.
Elek. Zeit., 10-1913, p. 1242.
Eng. Mag., 4-1913, p. 53.
G. E. Rev., 1912, p. 336.
Colorado Power Co., 100,000 volts.
Elec. Wld., 1-1910, p. 217, 6-1910, p. 1649; 6-1912, p. 1195, 1205.
Elek. Zeit., 10-1913, p. 1242.
Glas. An., 6, 7, 8-1913, p. 224, 5, 24, 51.
Lundquist, "Transmission Line Construction," p. 47.
Taylor, "Transformer Practise," p. 270.
Great Western Power Co., 100,000 volts.
Elec. Rev. & West. Elecn, 2-1913, p. 267.
Elec. Wld., 8-1909, p. 471; 9-1909, p. 657, 712; 6-1912, p. 1193, 1195; 6-1913, p. 1277.
Elek. Kr. & B., 1910, p. 160.
Elek. Zeit., 10-1913, p. 1242.
Eng. Mag., 3-1910, p. 851, (vol. 38).
Eng. News, 5-1909, p. 516.
G. E. Rev., 1911, p. 6, 1912, p. 336; 1913, p. 352.
Glas. An., 6, 7, 8-1913, p. 224, 5, 24, 51.
Trans. A. I. E. E., 1911, p. 1994.
Taylor, "Transformer Practise," p. 270.
Southern Power Co., 100,000 volts.
Elec. Jl., 1911, p. 329.
Elec. Wld., 12-1907, p. 1241; 3-1910, p. 741; 7-1911, p. 17; 6-1912, p. 1195.

Elek. Kr. & B., 1911, p. 175.
Elek. Zeit., 10-1913, p. 1242.
G. E. Rev., 1909, p. 551; 1910, p. 24; 1912, p. 336; 1913, p. 352.
Eng. Mag. 4-1913, p. 53.
TRANS. A. I. E. E., 1908, p. 819; 1911, p. 1998.
Lundquist, " Transmission Line Construction," p. 48.
Shawinigan Water & Power Co., 100,000 volts.
Elec. Wld., 5-1912, p. 953, 1015; 6-1912, p. 1195.
Elek. Zeit., 10-1913, p. 1242.
G. E. Rev., 1913, p. 352.
Los Angeles Aqueduct, 100,000 volts.
Elec. Wld., 1-1912, p. 30; 5-1913, p. 955.
Eng. Rec., 8-1913, p. 476.
Tata Hydroelectric Co., 100,000 volts.
Elec. Wld., 6-1913, p. 1332; 11-1913, p. 950.
Engr., London, 4-1911, p. 402.
Engg., London, 10-1913, p. 547, 578.
Eng. Rec., 11-1913, p.
Societa Italiana di Elettrochimica, 88,000 volts.
D'Elettricita, 12-1913, p. 72.
Elec. Rev., Lond., 11-1910, p. 832; 12-1910, p. 913.
Elec. Wld., 9-1910, p. 741.
Elecn., Lond., 4-1910, p. 67.
La Rev. Elec., 8-1910, p. 119.
Appalachian Power Co., 88,000 volts.
Elec. Wld., 11-1912, p. 1141.
Eng. Mag., 4-1913, p. 53.
G. E. Rev., 1912, p. 336; 1913, p. 352.
Taylor, " Transformer Practise," p. 270.
Rio Janeiro Tramway Light & Power Co., Ltd., 88,000 volts.
Elec. Wld., 5-1909, p. 1153; 8-1909, p. 367; 4-1913, p. 897.
Elecn., Lond., 8-1911, p. 694.
Elek. Kr. & B., 1910, p. 584; 1911, p. 175.
Tasmania Hydroelectric & Metal Co., 88,000 volts.
Australian Mining Standard, 3-1911, p. 296.
Elec. Wld., 4-1912, p. 820.
Engg., Lond., 11-1910, p. 709.
Garcke, " Manual of Electrical Undertakings," vol. 17, p. 1437.
Mexican Light & Power Co., 85,000 volts.
G. E. Rev., 1912, p. 336.
Trans. A. S. C. E., vol. 58, 1907, p. 37.
Taylor, " Transformer Practise," p. 270.
Toronto Power Co., 85,000 volts.
Elec. Rev. & West. Elecn., 7-1906, p. 138.
Eng. Mag., 3-1910, p. 855.
Trans. A. S. C. E., vol. 65, 1909, p. 181.
Lundquist " Transmission Line Construction," p. 43.
Taylor, " Transformer Practise," p. 270.
Victoria Falls & Transvaal Power Co., 84,000 volts.
Jl. (British) I. E. E., 6-1913, p. 2.

Trans. So. Afr. I. E. E., 1913, p. 170.
Klingenberg, "Baugrosser Elektrizitaetswerke," p. 177.
Energia Electrica de Cataluna, 80,000 volts.
Engr., Lond., 10-1912, p. 384.
Z. V. d. I., 11-1912, p. 1791.
Swedish State Railways, 80,000 volts single-phase.
Elek. Kr. & B., 11-1913, p. 658; 3-1914, p. 161.
Katsuragawa Denryoku Kabushiki Kaisha, 77,000 volts.
G. E. Rev., 1912, p. 336.
Southern California Edison Co., 75,000 volts.
Elec. Wld., 8-1907, p. 277, 317, 359, 401; 10-1909, p. 1039; 6-1912, p. 1190, 1195.
Au Sable Electric Co., 72,000 volts.
Elec. Wld., 11-1906, p. 841, 9-1907, p. 528.
Elek. Zeit., 1909, p. 478.
Societa Generale Elettrica dell'Adamello, 72,000 volts.
Elecn., Lond., 7-1912, p. 608, 649.
Engr., Lond., 9-1912, p. 293, 319, 349, 373, 401.
Eng. News., 12-1911, p. 764.
Montana Company, 70,000 volts.
Bull. A. I. M. E., 8-1913, p. 1907.
Elec. Wld., 7-1901, p. 53; 5-1908, p. 1088; 8-1910, p. 432.
Elek. Kr. & B., 1911, p. 175.
Eng. News, 10-1910, p. 430.
Trans. A. S. C. E., vol. 50, 1903, p. 212.
Taylor, "Transformer Practise," p. 270.
Hidroelectrica Espanola Molinar, 70,000 volts.
Elek. Zeit., 1911, p. 535, 561, 586, 766.
Pennsylvania Water & Power Co., 70,000 volts
Elec. Wld., 10-1910, p. 929; 5-1911, p. 1125; 8-1912, p. 395; 11-1913, p. 924; 2-1914, p. 314.
Eng. Mag., 3-1910, p. 855; 4-1913, p. 53.
G. E. Rev., 1912, p. 36, 336, 658; 1913, p. 352, 389, 390.
Swedish State Railways, 70,000 volts.
Die Turbine, 3-1911, p. 202.
Elek. Kr. & B., 1912, p. 126, 763.
Engr., Lond., 5-1912, p. 587.
Ming. & Eng. Wld., 5-1912, p. 1085.
City of Winnipeg, 66,000 to 72,000 volts.
Elec. Rev. & West. Elecn., 12-1911, p. 1119.
Elecn., Lond., 3-1912, p. 831, 870.
Engg., Lond., 7-1912, p. 107, 143.

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PROVISIONAL SPECIFICATION FOR INSULATOR TESTING*

COVERING INSPECTION AND TESTS OF HIGH-TENSION LINE INSULATORS OF PORCELAIN, FOR OVER 25,000 VOLTS

The present provisional specification was approved and recommended by the Power Transmission Committee of the American Institute of Electrical Engineers, February, 1915.

SPECIFICATION

Introductory:

This specification covers certain methods of test and inspection which have been found well suited for testing high-tension line insulators for use under the ordinary conditions of power transmission work. It is expected to serve as a skeleton or model specification and may be supplemented by such additional provisions as may be appropriate for any particular case.

Certain portions of the specification are added as a guide where designs are to be offered by several bidders for competitive tests. In such a case bidders will understand from the specification all the requirements they must ultimately meet if their bids be accepted.

GENERAL SPECIFICATION COVERING ALL TYPES OF INSULATORS

1. a. This specification is intended to cover the checking of the design and the testing and the inspection of the factory output, of.....porcelain insulators, cat. No..... of.....Company; to be manufactured for the .....Company.

*This specification was revised in February 1915 and is printed here in its amended form.

b. The operating voltage is.....and the frequency is.....

c. Definitions: By "insulator" is meant the complete insulator or group of insulating members including all the parts necessary to support the conductor from the crossarm or on the pin as the case may be.

By "unit" or "unit insulator" is meant a suspension insulator element complete, having a metal cap and pin.

By "shell" is meant a single porcelain piece without cement or cap or pin.

2. *Drawings:*

A dimensioned drawing shall be furnished showing the complete insulator and metal parts, or, if the insulators are built up or composed of a string of units, showing the details of a unit and all the clearances between units and metal parts.

3. *Inspection:*

The maker will give to the purchaser or his representative such access to his works at all times during working hours as is reasonable and necessary to determine the suitability of material to be supplied, and shall furnish all necessary apparatus, labor, and other facilities for making the tests herein called for without cost to the purchaser. All good insulator units destroyed in the tests here called for are to be paid for by the purchaser at the contract price.

All insulators are subject to final inspection, test and acceptance at maker's factory.

Neither the inspection nor waiving of inspection nor the purchaser's acceptance will relieve the maker from obligation to furnish material in accordance with this specification.

4. *Design:*

All insulators shall be designed as far as may be practicable to fail by flash-over and not by puncture under excess voltage tests, especially under impact tests.

Insulators shall be of robust construction and design so as not to be easily injured in handling.

Explanatory Note:

The ultimate criterion of the merit of an insulator is its performance in service and the best available measure thereof is its behavior under definite tests. However, as no practicable tests actually reproduce service conditions, for example in the matter of high-frequency voltage or deposits of dust, criticism on theoretical grounds is valuable, and, other things being equal,

preference should be given to the insulators most closely conforming to theoretically best designs.

Altitude:

Careful attention in specifying flash-over voltages should be given to the fact that for varying altitudes the breakdown strength of air varies approximately though not exactly as the barometric pressure.

Metal Parts

5. *Corrosion:*

All metal parts shall be of non-corrodible material or shall be galvanized or sherardized in accordance with the specifications for galvanizing prescribed by the joint committee of the National Electric Light Association in its Specification for Overhead Crossings of Power Lines Above Telephone and Other Low-Voltage Lines. Surfaces shall be free from roughness or projecting points; bearing surfaces shall be smooth enough not to injure cables.

6. *Factor of Safety:*

Metal parts shall have a factor of safety of at least three over the maximum stress that they receive in service, except that with pins for pin type insulators the factor may be reduced to two where a higher factor is impracticable. The maximum service strain is here agreed upon as————lb.

Porcelain

7. *Quality:*

All porcelain shall be dense and homogeneous as is best adapted to high-tension insulator requirements, free from injurious cracks, blisters and flaws or other defects that would render it unfit for use in insulators. The burning of all porcelain sections shall be done so as to insure even vitrification but shall not render the porcelain unduly brittle. The surface shall be smooth and uniform and the body of the porcelain shall be moisture-proof.

8. *Glazing:*

The glazing shall be of.....color and of a reasonably uniform shade, smooth, hard and continuous over all surfaces except those to be in contact with the cement. It shall be unaffected by weather, ozone, nitric acid, nitric oxides, alkali dust, or sudden changes in temperature over the atmosphere range.

9. *Absorption: Explanatory note.*

While imperviousness of the porcelain to moisture is of

supreme importance, no satisfactory test of this quality is known.

Cement

10. *Assembling:*

All cemented joints between insulator parts shall be carefully made, using for this purpose the best grade of neat Portland cement, thoroughly mixed, and plentifully supplied with moisture during setting. The assembly shall be so done that no hollows or voids will be left between the cemented surfaces. All superfluous cement must be cleaned off of the insulator before crating.

Electrical Testing

Note. Sections 11 to 15 inclusive are particularly applicable to competitive tests and to tests the results of which are to be compared to similar tests made with other testing apparatus. In cases where merely a comparative study of different designs of the same make is to be made, all tests being carried out on the same testing apparatus, it is usually satisfactory to use the standard test apparatus of a first-class maker.

It should be definitely stated in the contract whether sections 11–15, inclusive, are to be adhered to or not.

11. *Wave Form:*

The wave form of the generator shall be a true sine curve within the limits specified for generators by the Standardization Rules of the American Institute of Electrical Engineers and may be checked by the methods therein prescribed.

12. *Control of Voltage:*

The voltage shall be controlled in such a way as not to distort the wave form.

One satisfactory method of control is the use of a regulator consisting of a shunt resistance connected directly across the low-voltage side of the transformer, and a series resistance in the supply. The shunt resistance must always bypass at least five (5) times the exciting current of the transformer. The principal control is effected by the series resistance. This method is often spoken of as the potentiometer method.

13. *Measurement of Voltage:*

The method of measuring the voltage on the test circuit shall be that method recommended by the American Institute of Electrical Engineers, covering such cases.

14. *Kilovolt-Ampere Capacity of Testing Apparatus:*

The kilovolt-ampere capacity of the testing apparatus, in-

cluding any series resistance used, is important, for the leading current taken by the insulators tends to alter the voltage of the test apparatus. The maximum current taken from the test apparatus shall not be so great as to distort the voltage wave more than permitted for generator electromotive force waves by the A.I.E.E. Standardization Rules.

15. *Surrounding Conditions During Tests:*

In *design checking* tests of insulators having an operating voltage not exceeding 75,000 volts, no object other than leads and supports should approach nearer than 6 ft. (1.8 m.) to the insulator. For insulators having a higher operating voltage, the conditions for the "design test" of complete insulators should be made as nearly as practicable the same as the conditions of actual service as regards the grounding of one side of the insulator and the arrangement and distance of grounded objects in the neighborhood. A conductor of 6 ft. (1.8 m.) or more in length, extending equally on both sides of the clamp, should be used to represent the transmission wire.

NOTE—In these tests the walls of the room will ordinarily introduce a very serious departure from the conditions of outdoor service. Open-air tests where feasible are preferable from this point of view.

Routine tests, not being on complete insulators or insulator strings, do not require these precautions.

16. *Frequency:*

Tests should be made at the frequency at which the insulator is to be used. Where special agreement is made tests may be made at 60 cycles on insulators intended for use on higher and lower frequencies. No error of a serious magnitude will be expected within the range of 25 to 133 cycles.

17. *What Constitutes a Breakdown or a Flash-over:*

An insulator is said to "fail" or "break down" under a voltage test whenever a puncture occurs in any part of the insulator. It is said to flash over when a discharge of any sort passes all the way from one terminal to the other, since such a discharge would be followed by an arc on a power line.

Local breakdown, either corona or local sparks, while an important symptom, indicating severe local stress, does not constitute a flash-over. The weight to be given to such local breakdown, however, is a matter of judgment.

18. *Rain Tests:*

Water should be sprayed on the insulator at a uniform rate averaging 1 in. (2.5 cm.) depth in 5 minutes, and should be reasonably uniformly distributed over the whole insulator. The rate of precipitation shall be measured by collection of water in a pan at the location of the insulator, the insulator being removed. A fairly satisfactory spray in the form of a fine mist can be obtained by some forms of spray nozzles where pressure is available.

The spray shall strike the insulator at an angle of approximately 45 deg. with the vertical.

The water used shall have a high specific resistance, not less than 5000 ohm-inches (12,700 ohm-centimeters). Pure water may often be obtained from condensed steam or melted ice, preferably artificial ice, or rain. Municipal water supplies are often so impure as to seriously impair the performance of the insulator on the wet flash-over.

When insulators are to be used in localities subjected to salt spray or alkali or acid mists, or to conditions producing dew deposits, special tests may be agreed upon.

19. *Puncture Under Oil:*

Tests on a certain percentage of insulator units, ordinarily not exceeding $\frac{1}{4}$ of one per cent, should be made to determine the ability of the insulator to resist puncture and to measure the uniformity of the product. This test is best made by submerging the insulator in oil.

For this test each suspension insulator unit should be completely assembled with its standard metal parts.

With pin type insulators there should be attached to the head of the insulator wires representing the tie and line wires, and a metal pin should be placed in proper manner in the pin hole.

The test voltage should then be applied to the metal parts in each case. The puncture value obtained under these conditions should not be less than 150 per cent of the dry flash-over voltage and should, where possible, be much higher. In the case of suspension units a factor approaching 200 per cent has sometimes been obtained.

The puncture voltage that must be met in the actual tests (§25) should be here specified for each contract, viz., ... volts.

In making the test, apply to the insulator a voltage 30 to 40 per cent below the dry flash-over value and then raise the voltage gradually or by steps, until puncture occurs, at a rate of

about 10,000 volts per second. The puncture value of porcelain is very sensitive to the length of time voltage near the maximum is applied; the puncture voltage may be lowered as much as 20 per cent by long-continued application of the test voltage.

20. *Series Spark Gap:*

In routine testing, it is well to have a short air gap between each insulator under test and the testing line, that the character of the charging current may be judged by the appearance of the arc.

PIN TYPE INSULATORS

21. *Inspection:*

All parts shall be inspected before assembling.

22. *Routine Tests. Electrical Tests Before Assembling:*

All insulator shells, before being assembled, shall be tested for three minutes at the voltages given in the following table. Should any shell be punctured in the last minute of test, the test will then be continued, after the removal of the punctured piece, until no puncture occurs in one full minute of test. These tests are to be conducted by inverting the parts in pans of water and placing water inside the several pieces, the potential then being applied to the two bodies of water.

NOTE. The water both inside and outside shall be filled to within one quarter of an inch of the highest point to which the later applied conducting parts, including cement, will extend.

The individual tests in the various shells shall be as follows:

Head.....	volts
Second Shell.....	"
Third Shell.....	"
Fourth Shell.....	"
Center.....	"

23. *Routine Tests—Final Electrical Test:*

All completed insulators shall be tested according to one or the other of the four following tests. One of these tests should be definitely specified for each lot of insulators tested under these specifications.

a. The insulators in groups shall be subjected to a voltage steadily applied just below the flash-over voltage for a period of three minutes. The voltage shall be held at such a point that a flash shall occur over some insulator of the set occasionally, but not more often than once in three seconds. This test involves a steady voltage stress and gives an opportunity for the heating up to the puncture point of any spots in the porcelain which may be sufficiently defective. For this test it is therefore objection-

able that there should be frequent flashing over, as each flash-over presumably removes the potential from all insulators for one alternation.

If an insulator of the group punctures during the last minute of the test, the test shall be continued until one full minute elapses without a puncture.

b. The insulators in groups shall be subjected to a voltage in excess of the flash-over voltage so that a continuous succession of flash-overs exists, this being continued for a period of two minutes. This test is intended to introduce the effect of impact and consequently continual flash-over is necessary.

c. The insulators in groups shall be given test (a) above, followed by test (b). The first test may be changed into the second by merely raising the potential without removing the voltage. In this case the time of the second part of the test should be reduced to one minute.

d. This test is the same as test (b) above, except that instead of applying this testing to insulators in groups, the insulators shall be tested singly and the voltage continued for a period of 20 seconds.

NOTE. In all the tests (a), (b), (c) and (d), above, it is important that the current be so limited in volume that no power arc shall follow a flash-over, as otherwise the voltage will be substantially removed from the insulators during the continuance of the power arc.

24. *Design Test—Mechanical:*

The following design test shall be made on enough complete insulators, usually not exceeding ½ of one per cent, to determine the behavior of the design and the uniformity of the product.

The insulators shall be capable of withstanding for 15 seconds without signs of distress a pull of..... lb. (..... kg.) applied at the tie-wire groove in a direction at 90 deg. with the axis of the insulator and pin. For the purpose of making this test, the insulator shall be mounted on the pin to be used in service. In case of failure the question as to whether the insulator or the pin is at fault shall be determined by testing again with a solid steel pin turned from a piece of round steel of such dimensions that this piece of steel acting as a pin for the insulator will not bend under the above-mentioned load.

It is desirable that a number of insulators be tested to destruction to show approximately the margin in mechanical strength.

25. *Design Tests—Electrical:*

The following design tests shall be made on enough complete insulators to determine the performance of the type. The insulator shall stand without failure:

a. A test for *flash-over, dry,* of three times the potential between line wires, applied for one minute.

b. A test for *flash-over, wet,* of not less than two times the potential between line wires, applied for one minute.

c. Puncture test under oil shall be made as specified under §19 above.

SUSPENSION TYPE INSULATORS

26. *Routine Tests—Electrical Test Before Assembling:*

All insulator shells shall be tested according to one or the other of the three following tests. One of these tests should be definitely specified, for each lot of shells tested under this specification.

a. The shells in groups shall be subjected to a voltage steadily applied just below the flash-over test for a period of three minutes. The voltage shall be held at such a point that a flash shall occur over some shell of the set occasionally but not more often than once in three seconds. This test involves a steady voltage stress and gives an opportunity for the heating up to the puncture point of any spots in the porcelain which may be sufficiently defective. For this test it is therefore objectionable that there should be frequent flashing over, as each flash-over presumably removes the potential from all insulators for one alternation.

If a shell of the group punctures during the last minute of the test, the test shall be continued until one full minute elapses without a puncture.

b. The shells in groups shall be subjected to a voltage in excess of the flash-over voltage so that a continuous succession of flashes exists, this being continued for a period of two minutes. This test is intended to introduce the effect of impact and consequently continual flash-over is necessary.

c. The shells in groups shall be given test (a) above, followed by test (b). The first test may be changed into the second by merely raising the potential at the end of the first test. In this case the time of the second part of the test should be reduced to one minute.

NOTE 1. In all the tests (a), (b) and (c), above, it is important that the current be so limited in volume that no power arc

shall follow a flash-over, as otherwise the voltage will be substantially removed from the shells during the continuance of the power arc.

NOTE 2. In making these tests the insulator shells are to be inverted in a pan of water and water placed in the inside. The water both inside and outside shall be filled to within one quarter of an inch of the highest point to which the later-applied conducting parts, including cement, will extend.

27. *Routine Test—Mechanical Test:*

After at least ten days setting of the cement, all units shall withstand for 3 seconds without signs of distress a mechanical pull of ..... lb. (..... kg.), in line with the axis of the insulator. Insulators may be given this test after a shorter period of setting, at the risk of the maker.

28. *Routine Test—Final Electrical Test:*

All completed insulator units shall be tested according to one or the other of the four following tests. One of these tests should be definitely specified for each lot of insulators tested under this specification.

a. The insulator units in groups shall be subjected to a voltage steadily applied just below the flash-over test for a period of three minutes. The voltage shall be held at such a point that a flash shall occur over some unit of the set occasionally but not more often than once in three seconds. This test involves a steady voltage stress and gives an opportunity for the heating up to the puncture point of any spots in the porcelain which may be sufficiently defective. For this test it is therefore objectionable that there should be frequent flashing over, as each flash-over presumably removes the potential from all units for one alternation.

If a unit of the group punctures during the last minute of the test, the test shall be continued until one full minute elapses without a puncture.

b. The insulator units in groups shall be subjected to a voltage in excess of the flash-over voltage so that a continuous succession of flashes exists, this being continued for a period of two minutes. This test is intended to introduce the effect of impact and consequently continual flash-over is necessary.

c. The insulators in groups shall be given test (a) above, followed by test (b). The first test may be changed into the second by merely raising the potential at the end of the first

test. In this case the time of the second part of the test should be decreased to one minute.

d. This test is the same as test (b) above, except that instead of applying this testing to units in groups, the units shall be tested singly and the voltage discharges continued for a period of 20 seconds.

NOTE. In all the tests (a), (b), (c) and (d) above, it is important that the current be so limited in volume that no power arc shall follow a flash-over, as otherwise the voltage will be substantially removed from the insulators during the continuance of the power arc.

This test shall be made after the mechanical test above prescribed, §27.

29. *Design Tests—Electrical:*

The following design tests shall be made on enough complete assembled insulators, not exceeding ¼ of one per cent, to determine the performance of the type.

a. A test for *flash-over, dry,* of one insulator unit having its normal position in the string and of a complete insulator string consisting of ..... units, of ..... volts, and..... volts respectively, applied for one minute.

b. A test for *flash-over, wet,* of a single insulator and of the string, of ..... volts and ..... volts respectively, applied for one minute.

c. The puncture test under oil shall be made as specified under §19 above.

It is preferable that the arc-over of the complete insulator when the test voltage is sufficiently raised shall be over the insulator as a whole and shall not be over the individual elements.

30. *Design Tests—Mechanical:*

The following design test shall be made on enough complete insulators, usually not exceeding ¼ of one per cent, to determine the behavior of the design and the uniformity of the product.

After at least two weeks setting of the cement, the insulators to be tested shall withstand for 15 seconds without signs of distress a pull of ..... lb. (..... kg.) in line with the axis of the insulator.

It is desirable that a number of these insulators be pulled to destruction to show approximately the margin in mechanical strength.

APPENDIX

The following tests are recommended as desirable where appro-

priate. They are not incorporated in the above specifications as experience with them is not yet sufficiently broad.

31. *Uniformity Puncture Test:*

Twenty-two single insulators, chosen at random from stock, which have passed all routine tests, shall each in turn be punctured under oil as provided for oil tests in §19 above. Any twenty of these values of puncture voltage shall then be selected by the maker. The difference between the maximum and minimum of these twenty puncture voltages must not be more than 20 per cent of the average voltage. This test should be repeated with one or more additional groups of 22 disks, not exceeding in the aggregate ½ of one per cent of the total, enough to determine the uniformity of the product. In case of failure of the lot to pass this test, the other insulators from the same burnings shall be tested as specified under §28, but for a period 5 times that there specified.

32. *Design Test—Impulse Test:**

Some form of impact or high-frequency test is of the greatest importance in testing high-voltage insulators, at least for the design tests. Two or three forms of such tests have been proposed, and it is expected that a supplement to this specification will be issued when these tests have been sufficiently standardized.

33. *Design Test—Combined Mechanical and Electrical Test:*

The following design test should be made upon enough insulators to determine the performance of the design and the uniformity of the product.

An insulator placed in an insulated testing machine and impressed with a voltage just under or just over the flash-over voltage (as may be agreed upon), shall be subjected to a gradually increasing mechanical pull until puncture occurs.

The insulator should not puncture at less than twice, or, preferably, three times the maximum pull to which the insulator is to be subjected in service, as fixed in §6 above.

34. *Uniformity—Brittleness Test, Applicable Especially to Suspension Insulators:*

The following uniformity test should be made upon enough insulator units to determine the performance of the design and the uniformity of the product.

A completed insulator unit which has passed all routine tests

*For an example of the application of such a test see paper by Imlay and Thomas, TRANS. A. I. E. E. Vol. XXXI, 1912, p. 2121.

shall be placed in ice water and the temperature of the water raised to boiling. The heating should not begin until after the insulator has been in ice water 60 minutes to permit all parts to come to the same temperature. The water should then be heated at a uniform rate of about one degree cent. per minute. After remaining at boiling temperature for 30 minutes the unit may be removed and should afterward be tested either by the measurement of its insulation resistance, using one or two thousand volts for the measurements, or by the standard routine electrical test (§28), or both.

35. *Percentage of Failure in Routine Tests.* The percentage of punctures in the electrical tests is a rough measure of the burning of the porcelain and the care in manufacture. A relatively large percentage of failures, perhaps over 5 per cent, suggests under-firing. It is recommended that the following modification be applied to routine tests §23 and §28:

"When the percentage of punctures in any group of insulator units or shells under test simultaneously, exceeds 5 per cent, the length of the time of application of the test voltage shall be doubled for that group".

DISCUSSION ON "SPECIFICATION FOR INSULATOR TESTING—COVERING INSPECTION AND TESTS OF HIGH-TENSION LINE INSULATORS OF PORCELAIN, FOR OVER 25,000 VOLTS" (ENGINEERING DATA SUB-COMMITTEE), DETROIT, MICH., JUNE 25, 1914.

Percy H. Thomas: Last year, the High-Tension Transmission Committee presented a "sample" or "model" or "skeleton" specification, as it might be called, for the testing and inspection of high-tension porcelain insulators. This has been quite extensively remodeled during the present year, without greatly changing the fundamental ideas of the specifications. Presumably this discussion will be the last chance for any effective criticism. I wish to open the subject by giving a few words of explanation in answer to a number of the suggestions which have been made.

I will call attention first to the fact that the high-tension insulator industry has developed under existing conditions, until at the present time it has reached large proportions. These insulators are all tested and used according to certain customary methods which are now well understood and generally accepted. It is not practicable for the Institute to step in and pass a resolution saying that hereafter the industry shall change about and follow some specification which it would present, radically different from the former practise. If our specification is to be used at all, it must be close enough to present methods, so that it can be followed without upsetting the general practise of the industry. This is our first limitation.

The second limitation is the fact that the manufacturers of insulators have their own electrical testing apparatus and mechanical testing apparatus, and it is only a very small percentage of the insulators actually manufactured and used that are tested on any other apparatus. We now have in addition two or three laboratories, outside of the electrical manufacturing companies, where tests can be made, but they are not accessible to a very large number of the users of insulators, and our specification must be so drawn that it will fit into the particular installations of testing apparatus at the manufacturers' plants.

Another thing which limits the extent of change that may be embodied in the proposed specification is the fact that the tests which the purchaser usually makes on his insulators are an integral part of the manufacturing process of the manufacturing companies. The manufacturing companies rely on this inspection and test, to a large extent, to check up and eliminate and weed out the bad material from their product. We should draw our specification in such a way that this will continue to be the fact.

I will repeat, what perhaps you have forgotten, that the backbone of this specification was originally drawn by the engineers of one of the insulator companies. Mr. Peek also gave us a

model specification. Most of the meat of Mr. Peek's specification was put over into the manufacturer's specification.

Perhaps the greatest value of this testing specification is the stating in definite form for the *average* engineer those particular facts, those broad methods, those general characteristics, which the most experienced engineers have found to be the most helpful in selecting and testing insulators. There is a good deal of educational matter in the specification that has been seriously objected to by a number of those who have favored us with criticisms, and I can understand their point of view—it goes against their sense of proper form for a specification on which materials are to be bought to include explanatory sentences and general statements, but, looking at the matter from a broad point of view and considering the practical results to be obtained, it seems to me these educational interpolations are a very important part of the whole.

There is great objection on the part of some to the use of the words "design test" to describe those tests which are made on a few insulators to determine the characteristics of the type, as distinguished from the routine tests made on every insulator. From a certain point of view the design should, as the critics claim, be determined before the test specification is adopted. However, the actual tests given in the specification as design tests should be made as called for in most cases, so that it reduces to a question of terms, and the term used is frequently used and I know of none better.

One of the suggestions that comes most frequently is that we specify the minimum size of transformer capacity that is safe for testing insulators. The necessity of using large-capacity transformers occurs only when comparative tests are to be made on different transformers or where for some other reason sine wave form is important. Ordinarily for routine tests it is desirable to limit the capacity of the testing transformer to prevent arcs on the insulators. The manufacturers of insulators have transformers of limited capacity installed, some of them of peculiar design from the point of view of power transformer design, and most of them use some means of limiting the capacity, either series resistance or series choke coils, or weakening the field of the generator.

Some one asked for a specification as to the quality of oil in which to make the oil puncture test, but I hardly think that is necessary. There is no trouble to get the insulator to puncture under oil, rather than flash over, and I cannot imagine that the quality of the oil would make much difference in the puncture quality of the porcelain.

I would call attention to the so-called combined electrical and mechanical test in the appendix. This test calls for the application of mechanical strain while the electrical potential is on. You will remember last year at Cooperstown Mr. Nicholson gave us some data showing that certain insulators punctured with less than half their normal puncture value when mechanical strains

of less than half the ultimate strength were impressed upon them. The year past has shown an investigation of this matter and a very great improvement. The test is easily applied. One manufacturer has a wooden arm testing frame, and puts voltage on a single insulator, allowing it to flash over, or he applies the voltage just below the flash-over, as may be desired, and gradually brings up the mechanical pressure until the insulator punctures.

E. E. F. Creighton: During the last three years we have given considerable attention to this matter of testing insulators, and I wish to take it up from a different point of view from that of the committee. I think the specifications are very desirable in the form in which they are now presented—they are made, however, from the point of view of the man buying insulators, and I shall take the point of view of the man using insulators.

Mr. Thomas has pointed out the difficulty that a user has in getting testing apparatus with which to test the insulators, the cost of it, and the details involved in carrying out the work. It was about one and one-half years ago, when a paper was presented on this subject in New York, that I had a very brief opportunity to show the oscillation transformer as a method of testing insulators, but the method has not been followed up in the proceedings of the committee—perhaps they lack definite information on the subject. I wish to give some instances of the use of this method, and point out some of its advantages. We started out with a problem such as many have at the present time—namely, the frequent loss of installed insulators. Forty of these insulators were removed from a line and taken to the laboratory, and there was applied to them a 60-cycle test, and four insulators punctured under this test at the flash-over potential. The 36 insulators left were then tested out with a high-frequency transformer and all failed. The diagram, Fig. 1, shows the well-known connections of an oscillating transformer set. The first circuit, at 110 volts, say, is stepped up to any convenient voltage, which I shall designate as 13 kv., which charges a condenser. The condenser sparks through an adjustable gap and coreless transformer. The coreless transformer gives a high potential at a high oscillating frequency. The insulator to be tested is connected across the high-voltage side of this transformer. The potential applied to the insulator is gradually increased by starting with the control gap very small and gradually screwing it open. By opening this gap carefully, any potential desired may be applied to the insulator at a frequency of several hundred thousand cycles

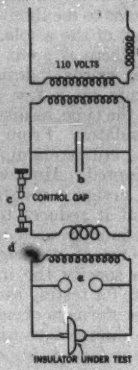

FIG. 1

per second, a convenient value being in the neighborhood of 200,000 cycles. The natural make-up of these transformers will give from 100,000 to 300,000 cycles. There is little need at present to question the proper value of this frequency, whether 100,000 or 200,000 cycles is to be used, because there has been such a tremendous step in going from 60 cycles to 200,000 cycles that an increase to 300,000 cycles is comparatively negligible in its effects. The higher the frequency the more the corona sparks follow the surface of the porcelain.

With apparatus of this kind we have made a great many tests in the porcelain factory itself, also the tests of insulators taken from lines and of insulators fresh from the manufacturers. In the early work it was feared that the test was too severe, and it was, since we did not take precautions at that time to bring up the voltage gradually by opening the control gap. It soon became evident that the voltage must be held under control and the adjustable control gap was therefore made an intrinsic part of the apparatus. An illustration of the value of the method is given by a series of tests which were applied to wet process porcelain bushings. Lots of one hundred bushings, as they came from the kilns, were tested on 60 cycles, bringing the potential up until it sparked over, then holding the potential a little below that value for one minute, and out of the one hundred there would be, as there always are, a few defective ones. They were then tested out on the high-frequency circuit. Going through different types of insulators, and insulators from different firings, there was a percentage of from zero to 17 per cent additional loss.

Another group of insulators was then taken, one hundred in a group, and tested on the high-frequency circuit first, and the defective insulators were removed as fast as they showed up. The insulators that were left after this high-frequency test were passed through a 60-cycle test; and although many hundreds of insulators were treated in that way, there was never a single case where an insulator which passed the high-frequency test was in any way damaged on the 60-cycle test. That, in itself, is proof sufficient that the high-frequency test is better than the 60-cycle test.

The next question arises—is it a fair test? At the present moment I am not going to discuss that, but simply say that the test can be made as reasonable or as severe as desired by the simple adjustment of the control gap. By opening the control gap to its widest value, super-spark potential may, of course, be thrown on the insulator and damage may result. For example, if the sparking potential of the insulator is 80,000 volts, it is easy enough to arrange the gap so as to throw on the insulator at the first instant a voltage of 175,000 volts. That value of voltage exists on the insulator during only the brief time necessary for the arc to creep around the surface from cap to pin. Such a severe test is not to be recommended as a standard test.

Testing just at and below the spark potential is both desirable and fair to porcelain of good design and material. This seems sufficient comment on the severity of test.

Every line at the present time has insulators on it that are old—perhaps only a dozen years old, but that is very old in the art of making insulators. At that time insulators were made very much like dinner plates, and very little attention was paid to the subsequent testing. I find that old insulators taken from a number of different systems are very liable to be in a condition that is sometimes designated as porous, due to underfiring. These insulators are necessarily weak electrically. The problem, then, of the operating engineers is not only how to buy good new insulators, but what to do with the old ones. It is usually impracticable to take down from the pole line all of the insulators and stand the loss which comes from mechanical accidents in handling and shipment to a laboratory to have tests made. Therefore, it is necessary for the engineers of a transmission company to be able to make tests, and not only make them themselves, but if desirable to make them on the insulators in place on the line. The oscillator form of testing, then, gives the possibility of having universally available a light, cheap and effective means of testing insulators, either new from the factory, or old, in service.

The question of kilowatt capacity for testing has been brought up by Mr. Thomas. In the oscillator sets the kilowatt capacity of the 60-cycle transformers is extremely small—1, 2 or 3 kilowatts—even a potential transformer has been used, although it cannot be used continuously, due to the overload. A very small kilowatt capacity in the 60-cycle circuit will sound unreasonable to those who contend that it is absolutely necessary to have a large generator and a large transformer in order to get reasonable results in testing, but that is not true in this case, for the actual power of this outfit, even with a small transformer, is considerably greater than any of the 60-cycle testing outfits that are in common use at the present time, without exception. The difference comes in this, that the energy is taken by the condenser at comparatively low power during a quarter-cycle of the generator wave. Although this period of time is of the order of 0.01 second, it is an extremely long time as compared to the time of discharge of the condenser. When the potential has risen to the maximum point of the 60-cycle wave, it breaks over the control gap. The full charge of the condenser will be given out at a rate which will depend upon the capacitance and the inductance of the oscillating circuit. As a matter of fact, the condenser is capable of giving out several thousand kilovolt-amperes for an instant, so there is no question about a sufficient kilowatt capacity.

In conclusion I wish to say one word in regard to one of the suggestions presented in the specifications, about uniformity—the valuable recommendation is that if a certain percentage of

the insulators fail the entire lot should be rejected. This ruling can be more efficiently applied if the insulators can be divided into lots corresponding to definite zones in a kiln and to definite firings.

Percy H. Thomas: How do you determine the voltage and the frequency on the high side of the oscillation transformer?

E. E. F. Creighton: The frequency is measured either directly by cymometer or calculated, and the calculations agree so accurately with the measurements that the easiest method is by calculation. The cymometer is an instrument as easy to handle as a wattmeter. Once the method of use is learned it is easy to handle. In the matter of potential there is some question; there is no way today of accurately measuring high-frequency potential. The potential as given by the proposed standard sphere gap is assumed to be correct. The limitation designated by Mr. Peek is to make the length of gap not greater than three times the radius. That is the only basis we have for the direct measurement of high-frequency voltage. Practically it is simply a matter of what equivalent gap will spoil an insulator. The spark potentials at arc-over voltage for 60 cycles and 200,000 cycles agree closely, in general.

Percy H. Thomas: There is no question that this method Professor Creighton has been telling us about, and which he fully described and demonstrated at the December, 1912, meeting in New York, is a powerful instrument of research, but I doubt if he would consider that it is quite definitely enough established to embody in the specification.

E. E. F. Creighton: This is as definite a test as some which have been put in the specification. I refer to the impulse test. The impulse test has been made a part of the appendix, and this test which I have shown is far better understood and can be made less dangerous than the impulse test.

Percy H. Thomas: That leads to a point I want to bring out, as to the relative characteristics of the test Professor Creighton has described and the impact test called for in the specification. The difference is this—the impact test of the specification is a shock test, a feeble shock, applied to the insulator, almost exactly paralleling the condition of service brought about by lightning and switching. It shows, if properly carried out, no element of heating. This test referred to by Professor Creighton, is, if I am not mistaken, entirely dominated by the heating effect produced by the high-frequency current; what I mean to say is this—when we have a high potential impressed on any insulator, the material of the porcelain is subject to an extreme pressure. Every time that test is reversed, a new element of heat is added. With the 300,000 cycles, you have 300 times the amount of heat generated, due to the expansion of material, that you do in the single shock. The net result is not only the heating of the insulator, but the heating of the air in the particular place where the interruption of potential is greatest. I do not think you

realize how quickly the dielectric strength of porcelain goes down as the temperature goes up. I cannot give definite figures. Two or three times the boiling point of water is enough to make a great difference in the insulation resistance of porcelain. It is the extent and degree of the heating of the dielectric material at that high frequency which is, it seems to me, the thing we must know more about before we can use this test. In actual service we do not get that condition—we get two or three impacts, but never sustained high frequency. It is putting a great premium on efficiency in a thing which, while it may be indirectly related to the serviceability of the insulator, is not necessarily related to it.

E. E. F. Creighton: I feel that this criticism is unjust, because it cannot be shown where the heating comes in. We can take an insulator of this kind and place it under the oscillation test for a whole minute, and all the time the spark discharges are streaming over the porcelain surface. It looks hot while the sparks are playing, but no appreciable rise in temperature is noticed after such a test by placing the hand on the surface. There is no doubt that a continuous strain applied at one point will heat the insulator. If one of these insulators is subjected to the continued voltage of an Alexanderson generator it is possible to make it red hot, but the application of the oscillator is different. There is a relatively long interval of rest between successive applications of high-frequency trains. The high potential is applied for a very small fraction of the total time. Judging from the many hundreds of tests we have made, I feel that the heating of the insulator, except in air spots where it is weak and where it ought to be heated, is entirely a negligible quantity.

Edward Bennett: I want to endorse most heartily what Mr. Creighton has said about the desirability of using impulse test circuits having such constants that fairly definite ideas can be formed of the rate at which the voltage across the insulator rises, and of the frequency of the applied stress across the insulator, provided the insulator under test does not flash over during the first half-cycle of the high-frequency oscillation.

The objection to the type of impulse circuit shown in Fig. 1 of the specification is that from the dimensions of such a circuit one can not determine very accurately the rate at which the potential rises across the insulator. This uncertainty arises from the fact that in the circuit shown in Fig. 1 in the specification,* even when used with fixed inductance, capacity and setting of the gap A, the rate at which the voltage rises across the insulator will depend upon the variable capacity of the different types of insulators under test. Suppose, however, that the type of circuit which Mr. Creighton has suggested is slightly modified by connecting across the secondary of the oscillation transformer, and in parallel with the insulator under test, a condenser having a capacity five or six times that of the insulator, as shown in Fig. 2 herewith. From the setting of the gap and the dimensions

*This diagram is not included in the revised specification.

of such a circuit, one may compute with a satisfactory degree of accuracy the manner in which the potential will rise across the insulator up to the instant at which breakdown or flash-over occurs.

A slight modification of the simple series circuit of Fig. 1 of the specification would eliminate the uncertainty due to the variable and unknown capacity of the different types of insulators under test, and would seem to render this circuit more satisfactory than the oscillation transformer connections advocated by Mr. Creighton. The modification of Fig. 1 of the specification is shown in Fig. 2. It consists in connecting the insulator under test in parallel with another plate condenser having a capacity about five times that of the insulator. The capacity of the 12 in. by 12 in. triple-petticoat insulators used on 40-kv. lines is about 2×10^{-11} farad from line wire to pin, and the capacity of a 10-in. single-piece suspension unit is about 3×10^{-11} farad from metal to metal. That is, the combined capacity of the condenser B and the insulator ought to be about 10^{-10} farad or approximately the same as the condenser C.

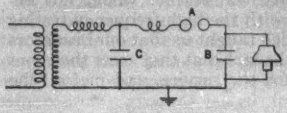

FIG. 2

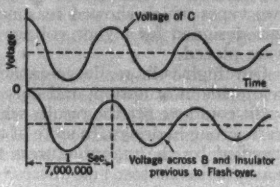

FIG. 3

If the coil L and the leads consist of about 30 ft. (900 cm.) of heavy copper, the inductance of the oscillatory circuit may be estimated at 0.01 millihenry. Such a circuit up to the instant of failure of the insulator will have a frequency of oscillation of approximately 7,000,000 cycles per second and the relation between the condenser voltages and time up to the instant of insulator breakdown will be as illustrated in Fig. 3. It is to be noted that the insulator, if it does not flash over during the first half-cycle, will be subject to a unidirectional pulsating voltage and not to an alternating voltage.

E. M. Hewlett: I would like to hear some discussion on the subject of the absorption test. Could not something in the nature of a year's guarantee be required? I have found insulators to fail from imperfect vitrification, which had passed all the different kinds of tests. Some of them fail in the course of a year, or six months, even, showing they have not been thoroughly vitrified, and still, to begin with, they will stand all the different tests. Until there is a test which will show definitely whether an insulator has been throughly vitrified, it would seem

as though the insulator should come under the same kind of guarantee as a piece of machinery, as they are very often used in connection with the switching devices, to support busbars, etc., and should be considered as machines in that case.

Farley Osgood: In our somewhat extended system of multiple operation of transmission lines, fed by large-capacity generating stations operating in parallel, we learned from our charted data on service interruptions that the chief initial cause was the insulator. All testing at normal pressure (13,000 volts) brought us no real knowledge of our difficulty, so testing apparatus for more than three times normal voltage (40,000 volts) with 1000-kw. capacity was installed. Tests with this taught us no more than we could learn with line voltage testing, so we had made a testing outfit which, by means of a Tesla coil and condensers, gave us a frequency approximating 250,000 cycles.

We brought in from our lines samples of all types of insulators in service, fifteen types in all, several of which were designed for operating at three times the voltage on which they were being used, and all but two types failed under our test, meaning that the insulator would puncture before it would arc over, and the two types which showed reasonable results were not the insulators designed for higher voltage than the service in which they were placed.

Our high-voltage, large-capacity transformer would not develop this information, and only with the high-frequency testing outfit could we get the results which taught us that our insulators were wrong in design, in spite of the fact that they were the types specified by the manufacturers for the service, and met all the manufacturer's test guarantees.

The result of our work has been a new standard insulator for our 13,000-volt service which is about the same size as our original insulator but has thicker petticoats and which will spill over before it will puncture.

An analysis of our difficulties showed that unquestionably our troubles were caused by the effect of switching, which takes place frequently in a large system with big stations in parallel, and which effects were from high frequencies, and therefore we feel that the high-frequency test is the most useful one of all. It is the test which tells the operating man what he wants to know, and should be made in addition to any other tests that a manufacturer thinks necessary to establish the mechanical perfection of his product, as the high-frequency test is really one on the design of the insulator, rather than its structure.

We now give every insulator a high-frequency test before it is placed in service, and a recent test of 13,127 pin type insulators showed a failure of 1.75 per cent, and of 2260 disk type 3.94 per cent of failure. While at first this may seem high, it is not really so, as the actual value of the insulators destroyed is small, and well worth while for the insurance of continuity of service.

The test is not expensive, is safe, and a crew of four men from

the line department, with one laboratory man to handle the test set and keep the records, can unpack, test, and repack 1200 insulators in an eight-hour day.

The high-frequency test, using the Tesla coils, we believe presents the following advantages:

1. An even distribution of corona over the entire surface of the insulator, searching out imperfections.

2. Failures under test are absolutely definite, being readily recognized by

(a) cessation of corona,

(b) abrupt change of tone of spark due to shortened path,

(c) steady discharge through point of failure.

3. The test does not require skilled labor, but can be conducted by anyone, after a little training, if his sight and hearing are normal.

We believe we have at last an equipment which can be made portable for use in the field in testing individual insulators in service without removing them from the line, the transmission voltage, of course, being removed, and we advise operating engineers to learn of the benefits to the service to be derived from such testing, by themselves, in addition to any test, or any guarantee, of any manufacturer, no matter what the type or line voltage of the insulator.

S. C. Lindsay: I want to take exception to what Mr. Thomas said about the impulse test being usually sufficient for insulators tested with high frequency. That test is not sufficient on delta-connected lines having no ground. Two disturbances occurred within the past year on the system with which I am connected, where arcing grounds lasted for two or three minutes, and several insulators were punctured each time. I should think it would be well to retain the high-frequency test so that insulators will meet these conditions.

Percy H. Thomas: They might get some sustained effect from the arcing ground—I do not know just how that would work out.

John B. Fisken: It occurred to me that I might give some information bearing on the subject of the rain test. I had occasion once to demonstrate that there was no danger to a person holding the nozzle of a fire hose, the stream from which was striking a line operating at 60,000 volts. While I was demonstrating that, I went a little further and tried to break down some of the insulators by spraying the stream on them. I hit every part of the insulators I could reach with that stream, and there was not the slightest sign of any breakdown. That satisfied me that a rain test was entirely unnecessary.

F. W. Peek, Jr.: Considerable has been said about "high frequency" testing and the effects of "high frequency" on insulators and insulation. Under this term are included without discrimination, continuous high frequency as from a generator, trains of oscillations from a Tesla coil, single impulses of exceed-

ingly steep wave front as from lightning, etc. The effects of these are entirely different. As the results of tests are all attributed to the same cause, "high frequency," there is naturally much confusion.

As an illustration, take an ordinary single suspension insulator unit with an arc-over voltage of 90 kv. and a puncture voltage of 120 kv. (under oil) at 60 cycles. If a continuous high frequency at 10 kv. and 100,000 cycles is applied from an alternator, the insulator will soon become hot because of dielectric loss, and crack. The destruction of this insulator is due purely to heating. If trains of high-frequency oscillations at the rate of about 100 trains per second are applied, arcs will play over the surface of the insulator if the voltage is sufficiently high. To cause the unit just to arc over, a voltage somewhere between 90 and 130 kv. (higher than 60-cycle arc-over) will be required. A sufficiently long application will cause the insulator to break down. An oscillatory voltage of say 200 kv. may be applied. The discharge over the surface will be heavier. Breakdown will occur in a very short time, due to over-voltage. This voltage is higher than the 60-cycle puncture voltage. Although this unit arcs over, it takes a finite but very small time for the air to break down and the arc to occur as each wave train starts. The time is too small for the porcelain to break down on one wave train. It is injured, however, and the effect is accumulative. A sufficient number of trains causes breakdown. If an impulse of very steep wave front, of say 500 kv., is applied, arc-over occurs along the surface. Perhaps ten such impulses may be applied without apparent damage. At the eleventh impulse breakdown occurs. Each impulse has caused damage during this very short time that it takes the arc to occur. A needle gap set at 150 kv. across the insulation to "limit" the voltage will not prevent ultimate breakdown. The various and apparently inconsistent effects due to "high frequency" are thus not altogether mysterious.

Such tests are extremely valuable as design tests, uniformity tests, etc., but great caution is necessary and a thorough understanding of what sort of "high frequency" it is, when these tests are applied to insulators that are later to be used on lines, as the first lightning stroke may be in effect the ninth or even the eleventh impulse noted above.

Many failures undoubtedly do occur, due to "high frequency," but there is at present too much of a tendency to use this explanation when the real cause is quite simple, perhaps only a mechanical one. A great many insulator failures, perhaps most of them, are *fundamentally* caused by mechanical cracking gradually taking place, due to poor mechanical design, internal strains, etc., or absorbed moisture. Naturally, failure occurs on these *weakened* units during a voltage rise, as by lightning impulse. Of course there are also some failures due to the accumulated effects of over-voltage impulses on good units.

I believe that most moderate-voltage lines, 20 to 60 kv., are under-insulated. These lines extend out into open country and are subjected to the same lightning voltages as the very high voltage lines. The insulators have the same factor of safety as the high-voltage lines, but in terms of operating voltage. This naturally is without meaning, as, assuming good insulators at the start, destruction is not caused by line voltage but by lightning. I have illustrated this further with a definite example in a discussion at the Pittsfield meeting, May 29, 1914.

Farley Osgood: We believe that an insulator should spill over before it punctures, giving the line the accompanying relief from the strains of switching changes which are constantly taking place; and an insulator of this type will act as an arrester on the line, as it were. The operating man wants his system to come back intact after severe strains, and much prefers the chance of a momentary interruption of service to the almost certain discomfort of the shake-up resulting from complete insulator failures.

Therefore, in this belief we feel that the high-frequency test is the only one which will assure the operating man that the insulator will perform as desired in this relation of spill-over to puncture.

We have proved that much can be learned from this test, that field work with such a testing outfit will anticipate many failures, and we have proved that it is cheap, and that it is safe.

In spite of all the theories to the contrary, such as we have just heard, I feel that the operating man has at last come into his own, in the matter of finding out some things about his insulators for himself, and doing it right at home, and I hope that the practicability of the results of these simple and easily made tests will be appreciated.

William B. Jackson: I want to ask a question relating to this matter, and that is, where the matter now stands, according to the researches and studies of the committee, in developing some suitable method of obtaining the capacity of the insulator, in the matter of mechanical shock, which has always seemed to be a rather important factor, although it has not been given very much consideration in tests.

Another question, which I presume has been studied by the committee, is whether there is any way by which the atmospheric effects may be accelerated in the passage of time upon the insulators. Guaranteeing an insulator for a year would be very small satisfaction, since insulators will run perfectly for two, three or as much as five years, and then break down.

Percy H. Thomas: The power of an insulator to hold a sustained load is now covered by a test in the specification, but I do not know any one who has proposed a test such as you indicate, and I do not know of any test that could be quantitatively expressed, so that an insulator would pass at 105 per cent and would not at 95 per cent. I do not know of any way by

which we could approximate the effect of the weather. I wish we knew more of the effect of alkali dust, salt spray and condensation in connection with the rapid changes of temperature. These things are important, but we do not know the manner in which to produce such conditions beforehand.

William B. Jackson: They would be fruitful fields of study. In the case of cement, for instance, we have an impact test; in the case of concrete and cement, we have an acceleration test which is very valuable in the case of a building under construction. It seems that a study of that particular phase of insulators may bring good results.

Percy H. Thomas: The effect of electrical impact can be tested, but, mechanically, it is difficult to tell how the insulator will be affected.

Presented at the 31st Annual Convention of the American Institute of Electrical Engineers, Detroit, Mich., June 25, 1914, under the auspices of the Committee on Prime Movers.

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PRESENT STATUS OF PRIME MOVERS

BY H. G. STOTT, R. J. S. PIGOTT AND W. S. GORSUCH

ABSTRACT OF PAPER

The paper brings out in a concise form the present status of heat engines and hydraulic turbines in commercial use today for the conversion of the energy found in fuel and water into mechanical power for the production of electric energy.

The various types are compared as to relative importance, capacity, efficiency, weight, cost and economy, which are illustrated by curves plotted on kilowatt basis.

(a) Reciprocating Steam Engine.
(b) Steam Turbine
(c) Gas Engine
(d) Oil Engine
(e) Hydraulic Turbine
(f) Finance and Economics

Curves are plotted showing the investment and fuel costs of the different heat engine units, on the basis of percentage of normal full load rating of machines.

THE Committee on Prime Movers has selected the following subdivisions of its subject, in order to cover the most important recent developments in the field of prime movers:

1. Reciprocating steam engine
2. Steam turbine
3. Gas engine
4. Oil engine
5. Hydraulic turbine
6. Finance and economics.

In order to show the present status of the art in a graphic manner, practically all of the data obtained have been plotted in curves which appear in the appropriate place in the text.

RECIPROCATING ENGINE

The reciprocating steam engine has, during the past five years, become practically obsolete for use in modern power stations. In the large new central station this engine is not even considered; but in small isolated stations it is still used to a considerable extent, especially where heating service is also handled. In small sizes, the engine still has some advantage in economy

over the small turbine, but the margin is getting continually smaller; some of the latest geared units being almost on equal terms. The non-condensing and bleeder turbines have offered a satisfactory substitute for the engine on heating service: the continuance of the engine in use is therefore chiefly due to the apparent inability of purchasers for isolated plants to realize that economy of steam is only one of the items constituting cost of power. The superior reliability, low maintenance, sustained original economy, and low attendance cost of the turbine generally overbalance the rather doubtful advantage in original economy of the small reciprocating engine.

Steam Turbine

The steam turbine is now at the head of the list of prime movers. The items of comparison with other prime movers are:

(a) Capacity
(b) Efficiency
(c) Weight
(d) Price.

Capacity and Efficiency. Usually the figure quoted as the measure of efficiency is the water rate or steam consumption per kilowatt-hour. Hardly any measure can be selected which is less satisfactory, since, unless the steam and vacuum conditions are stated, the water rate means nothing. Two turbines of exactly equal merits may be quoted as having very different water rates if one is operated on superheated steam with high vacuum, and the other wet steam and lower vacuum. To fix the merits of the design, a knowledge of the efficiency ratio (Rankine cycle) is necessary; and to fix the thermal efficiency, a knowledge of the steam conditions is needed—in other words, the heat drop available.

The water rate of a perfect Rankine-cycle engine is given as 3415 divided by the available adiabatic heat drop between initial and final conditions of the steam. Table I gives a few values for the commoner conditions in use. The efficiency ratio is equal to the Rankine-cycle water rate divided by the actual water rate of the turbine. The thermal efficiency and the water rate are both dependent upon the steam conditions, and can never be correctly compared except upon the same basis of pressure, superheat and vacuum.

The efficiency ratio is a measure of the goodness of the design, influenced somewhat by steam and vacuum conditions. The

TABLE I

HEAT DROP AND WATER RATES FOR 100 PER CENT RANKINE-CYCLE EFFICIENCY.

Press.	Dry steam.						100 deg. superheat.						150 deg. superheat.					
	28 in.		28.5 in.		29 in.		28 in.		28.5 in.		29 in.		28 in.		28.5 in.		29 in.	
	H.D.	W.R.	H.D.	W.R.	H.D.	W.R.	H.D.	W.R.	H.D.	W.R.	H.D.	W.R.	H.D.	W.R.	H.D.	W.R.	H.D.	W.R.
lb. per sq. in.	B.t.u. per lb.	lb. per kw.	B.t.u. per lb.	lb. per kw.	B.t.u. per lb.	lb. per kw.	B.t.u. per lb.	lb. per kw.	B.t.u. per lb.	lb. per kw.	B.t.u. per lb.	lb. per kw.	B.t.u. per lb.	lb. per kw.	B.t.u. per lb.	lb. per kw.	B.t.u. per lb.	lb. per kw.
165	324	10.52	338	10.09	355	9.61	345	9.89	360	9.47	378	9.03	353	9.66	368	9.27	387	8.82
190	331	10.30	348	9.80	364	9.37	356	9.58	369	9.25	387	8.82	365	9.35	379	9.00	398	8.57
215	341	10.00	354	9.63	371	9.19	363	9.40	376	9.08	394	8.66	373	9.14	387	8.81	406	8.41
240	347	9.83	361	9.45	378	9.02	371	9.19	385	8.86	403	8.46	380	8.98	396	8.61	413	8.24
kg. per sq. cm.	cal. per kg.	kg. per kw.	cal. per kg.	kg. per kw.	cal. per kg.	kg. per kw.	cal. per kg.	kg. per kw.	cal. per kg.	kg. per kw.	cal. per kg.	kg. per kw.	cal. per kg.	kg. per kw.	cal. per kg.	kg. per kw.	cal. per kg.	kg. per kw.
11.59	180.0	4.78	187.8	4.58	197.1	4.36	191.5	4.48	199.9	4.30	209.8	4.09	196.0	4.38	204.5	4.21	214.8	4.00
13.36	183.8	4.67	193.1	4.45	202.1	4.25	197.8	4.34	204.8	4.19	214.5	4.01	202.5	4.24	210.5	4.08	221.0	3.89
15.10	189.2	4.53	196.3	4.38	206.0	4.17	201.5	4.27	208.8	4.12	218.5	3.93	207.2	4.14	215.0	4.00	225.2	3.82
16.87	193.7	4.43	200.5	4.29	209.8	4.10	206.0	4.17	213.5	4.03	224.0	3.84	211.6	4.07	219.8	3.91	229.5	3.75

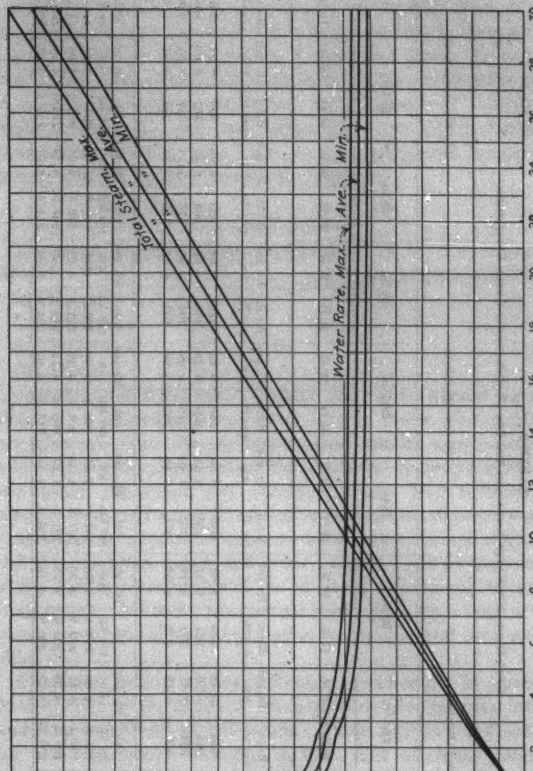

FIG. 1—STEAM TURBINES—TOTAL STEAM VS. CAPACITY—STEAM PER KW-HR. VS. CAPACITY

60 cycles, max. 24-hr. rating 50 deg. cent. rise; power factor 80 per cent, pressure 175 lb., superheat 100 deg. fahr; vacuum 28.5 in.

efficiency ratios of modern turbines differ much less from each other than the variation of water rates would lead one to suppose.

The efficiency ratio increases (a) with size, (b) with superheat, (c) with reduction of vacuum down to about 26 in. (66 cm.), (d) with reduction of pressure. Speed also affects efficiency ratio, either to increase or decrease it, depending upon the design and conditions. Thermal efficiency increases (e) with pressure, (f) with superheat, (g) with vacuum. It is evident that some of these conditions at least are incompatible with each other, and that the turbine having the best water rate may not have the highest efficiency ratio.

Fig. 1 shows water rates which may be obtained for various sizes of machines. For the standard conditions of 175 lb. (79.3 kg.) gage, 100 deg. superheat, 28½ in. (72.4 cm.) vacuum, the average value is that which will ordinarily be obtained for standard designs; but better or poorer rates may be obtained under special conditions, either of design for high efficiency, which increases cost, or of cheap construction, which usually means poor water rate.

Fig. 2 shows the Rankine-cycle efficiency ratios under the same conditions. For the same sizes of machine, 25-cycle generators will have the same water rate and efficiency ratios, as the variation in speed can be readily cared for without sacrifice of efficiency. The corrections for other steam and vacuum conditions must be applied to get the proper water rates,—these differing somewhat for different types. The usual superheat correction is one per cent improvement in water rate for each 10 deg. superheat between saturation and 100 deg.; one per cent for each 12½ deg. superheat between 100 and 200 deg. superheat. The vacuum correction varies considerably with different machines, and amounts to about 5 per cent improvement between 27 and 28 in. (68.5 and 71 cm.); 6 per cent between 28 and 29 in. (71 and 73.9 cm.) A better method is to use the total heat drop available in each case as a ratio applied to the water rate. An important feature influencing cost is the matching of generator and turbine. In many cases the turbine has its best water rate at the maximum 24-hour rating of the generator. For many purposes this is undesirable. The best water rate should occur at from 75 to 85 per cent of the maximum 24-hour rating of the generator; in other words, the turbine should be smaller than the generator.

The overload devices (extra nozzles in the case of impulse

turbines and by-passing in the reaction turbines) can be readily designed to take care of the loads up to 50 per cent in excess of the best water rate load in the turbine. The best water rate

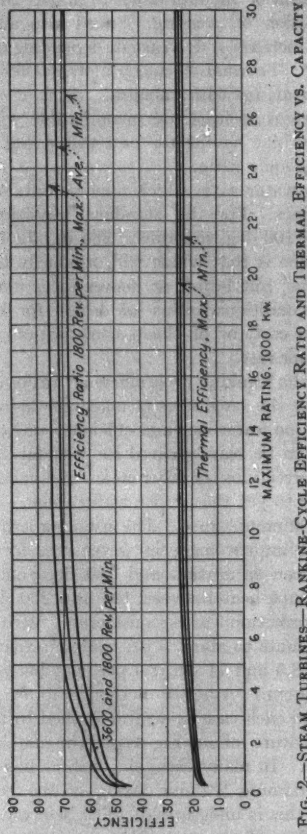

FIG. 2—STEAM TURBINES—RANKINE-CYCLE EFFICIENCY RATIO AND THERMAL EFFICIENCY VS. CAPACITY
Max. 24 hr. rating, 50 deg. cent. rise; pressure 175 lb.; superheat 100 deg. fahr.; vacuum 28.5 in.

reached by the turbine occurs just before these overload devices operate; and it is for the steam flow at these loads that the turbine proportions are designed. When the effect of auxi-

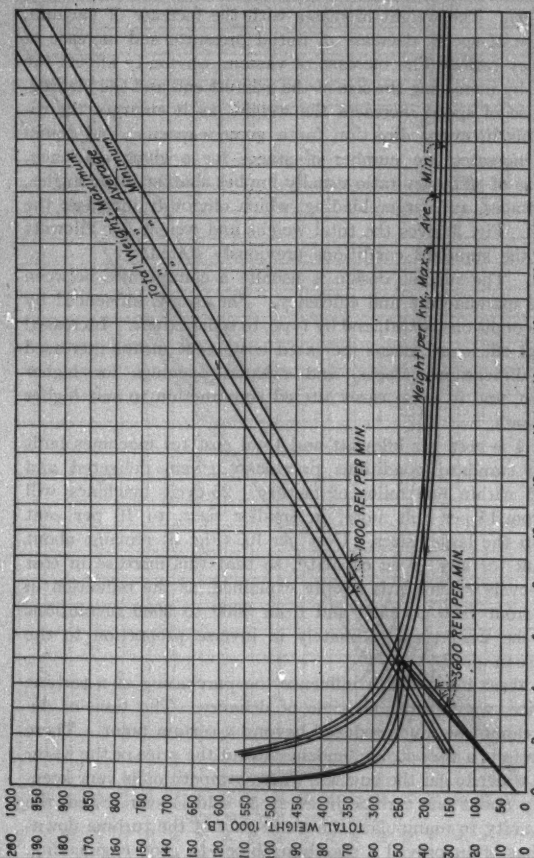

FIG. 3—STEAM TURBINES—TOTAL WEIGHT AND WEIGHT PER KW. VS. CAPACITY

60 cycles, max. 24 hr. rating, 50 deg. cent. rise; power factor 80 per cent, pressure 175 lb.; superheat 100 deg. fahr., vacuum 28.5 in.

liary steam consumption on the steam demand of the engine room is considered, it is evident that the under-sizing of the turbine to a small degree is desirable.

Weight. The weight increases with the increase of vacuum, decrease of speed, decrease of initial pressure, and increase of efficiency ratio. The increase of vacuum obviously affects the weight by increasing the size of the exhaust end and the blading. Decrease of speed increases the weight, as it enlarges the dimensions in every direction for a given capacity, and sometimes increases the number of stages for a given efficiency. Increase of efficiency ratio usually implies sharper blade angles, more stages, and larger blading, which obviously increases the weight. Fig. 3 gives the total weight and weight per kilowatt under the standard conditions previously stated.

Cost. The turbine design is usually a compromise between cost of manufacture and efficiency. The cost is influenced by steam conditions, speed, and by type, to some extent. Increased thermal efficiency means increased cost, as it means increased blade dimensions, stages, and exhaust openings for higher vacuum, and in some cases altered construction to suit higher superheats.

Fig. 4 is cost per kilowatt and total cost for machines built to the standard conditions previously given, delivered and erected within 600 miles of factory. 25-cycle machines will cost from 15 per cent more, in smaller sizes, to 10 per cent more in the larger sizes. Cost per lb. (Fig. 5) remains about constant for any given capacity, so that this increase in cost for 25-cycle machines is readily explained, as the reduction in speed from 1800 to 1500 and from 3600 to 3000 revolutions raises the weight approximately in inverse proportion to the decrease in speed.

The three items which influence the purchasing of a turbine are price, water rate and time of delivery. The time of delivery cannot be much reduced beyond a certain point. There is, therefore, a very strong tendency to cut the price or the water rate in order to get the business where competition is very keen. As only about one turbine in every 50 sold is ever tested, the opportunity to manipulate the water rate of the turbine downward has often proved a stumbling block to good engineering. The cost to manufacture any of the standard makes is not very different. The prices ordinarily will therefore be about the same. The tendency to cut the water rate below what can

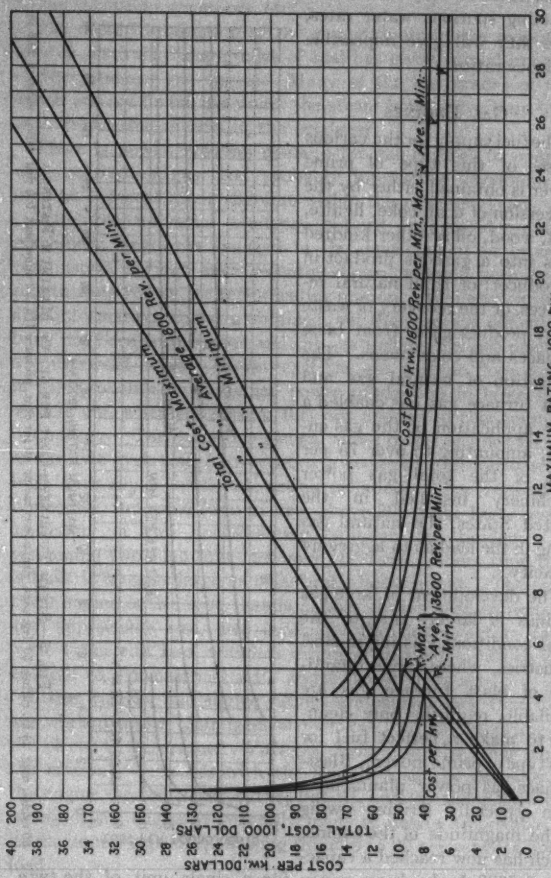

FIG 4—STEAM TURBINES—COST PER KW. VS. CAPACITY—TOTAL COST VS. CAPACITY

60 cycles, max. 24 hr. rating, 50 deg. cent. rise; power factor 80 per cent.; pressure 175 lb; superheat 100 deg. fahr.; vacuum 28.5 in.

actually be obtained can therefore only be checked by the engineer's watchfulness. Comparison with the Rankine efficiency ratio for any size machine is one of the safest means of detecting spurious water rates, since they will give impossible efficiency ratios.

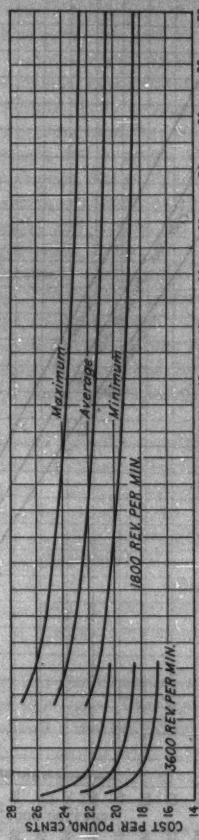

FIG. 5—STEAM TURBINES—COST PER LB. VS. MAXIMUM RATING

60 cycles, max. 24 hr. rating, 50 deg. cent. rise; power factor 80 per cent, pressure 175 lb.; superheat 100 deg. fahr., vacuum 28.5 in.

GAS ENGINES

The fuel supply for the various classes of this type of prime mover is obtained either by the conversion of coal, coke, lignite, peat, wood, oil or other kindred fuels into a gaseous product in a producer; or from natural resources, or the recovery of waste or by-product gases from blast furnaces and coke ovens. The utilization of natural gas and blast furnace gas has enabled a wide application of the gas engine, amounting to over 75 per cent of the total gas power machinery installed in the United States, the natural gas being in the lead as to aggregate capacity.

The development of large gas engines is largely due to the ideal conditions existing in steel industries, where large quantities of blast furnace gas are available, requiring only cleaning to make a perfect fuel for this type of prime mover. Blast-furnace-gas power plants have been especially striking owing to the magnitude of the engine, which has now reached a capacity of 6000 brake horse power for a single unit of the twin tandem type.

The main improvements in gas engines have been in the re-

inforcement of cylinder castings, simplicity of the cylinder, piston and rod construction, more efficient packing, adoption of the throttling governors, etc.

The rapid introduction of the gas-producer in the manufacture of gas from cheap grades of coal has given special impetus to the producer gas engine. Many of the low grades of fuel which are not fit for use under the steam boiler have been used with reasonable success in the producer.

There is now a growing demand for gas engines to operate with coke oven gas, and probably interesting developments may be expected along this line within the next few years.

With the universal tendency toward high-speed rotative machinery, engineers engaged in the development of internal combustion engines have recently shown renewed activity in substituting rotary for reciprocating motion. While much valuable information has been obtained, yet the practical difficulties have not been surmounted and the gas turbine has not reached a commercial stage. However, if the gas turbine does come, it will probably revolutionize power production in large steel centers and wherever natural fuel oils abound in this country.

Capacity. There are two general types of gas engines known as the two-cycle and four-cycle, or two-stroke and four-stroke, built with single- or double-acting cylinders, either vertical or horizontal, the usual form in sizes above 200 brake horse power consisting of two double-acting cylinders set tandem. By combining two such units we have the twin tandem type that is built in sizes as large as 6000 brake horse power. The four-cycle engine is the type that is almost always used in units of any appreciable size, and especially the double-acting four-cycle type with two cylinders arranged in tandem, which was brought to a commercial state about eleven years ago.

Steam turbine and engine ratings are usually such that they are worked under their most economical load at the rating of the electrical generator. With gas engines, on the other hand, the efficiency increases with the load beyond the capacity of the engine (see efficiency curve, Fig. 6), and for this reason the rating of the engine is generally made as nearly as possible to its maximum capacity, allowing from 10 to 20 per cent for overload.

The gas engine does not possess inherent capacity for overloads in the same sense in which the steam turbine and engine do, hence whatever overload it has, is allowed by the manu-

facturer. The maximum capacity of a gas engine is evidently reached when the cylinder has taken a full charge of mixture of the highest heat value and density, that is, containing the maximum B.t.u.'s (large calories) per cu. ft. (0.028 cu. m.). This being the case, it is evident that gas engines must accommodate themselves to variations in the quality of the gas. Assuming for illustration, that a 10 per cent overload is sufficient, an engine of 550 horse power maximum capacity would then be rated at 500 horse power.

The gas engine being fairly limited as to the power which may be produced in a single unit, there has developed on the part of some manufacturers a disposition to increase speeds. While high speeds have been used in steam turbine and engine practise, it should not be taken as a criterion in gas engine work, as the heavy masses involved in the reciprocating parts of the gas engine may become destructive and the result may be higher maintenance cost.

Efficiency. One of the characteristics of the gas engine which other heat engines do not possess is that the thermal efficiency remains fairly uniform over all ranges of sizes.

Fig. 6 shows representative curves of thermal efficiency and rate of heat consumption per kilowatt generated, for different percentages of normal full-load rating, of large four-cycle producer and natural-gas engines, no allowance being made for auxiliaries.

Many figures have been given of the thermal efficiency of the gas engine which vary materially, but we believe that the curve above referred to gives conditions generally met with in large gas engines, namely, 25.2 per cent on the basis of brake horse power, or 23.8 per cent on the basis of kilowatt-hours generated at full load rating. All curves of the gas and oil engines have been referred to the basis of kilowatt-hours generated, so as to be comparable with the steam turbine and engine.

The range of fuel consumption as guaranteed by American manufacturers for their engines at full load rating with different fuels varies from 9500 to 13,500 B.t.u. per brake hp-hr. (2394 to 3402 large calories) for producer gas, and 8500 to 15,000 B.t.u. per brake hp-hr. (2142 to 3780 large calories) for natural gas, or reducing to basis of kw-hr., 13,500 to 19,200 B.t.u. per kw-hr. (3402 to 4838 large calories) for producer gas, and 12,200 to 21,400 B.t.u. per kw-hr. (3074 to 5393 large calories) for natural gas. Blast furnace gas runs in the neigh-

borhood of 10,500 B.t.u. per brake hp-hr. (2648 large calories), or 15,000 B.t.u. per kw-hr. (3780 large calories) generated.

Weight. The operation of the gas engine involves high temperatures and pressures suddenly applied to the working parts, consequently this class of prime mover is inherently massive.

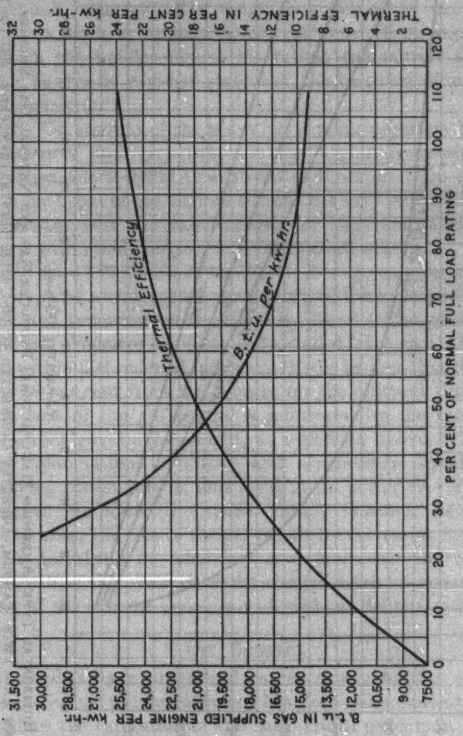

FIG. 6—REPRESENTATIVE CURVES OF LARGE GAS ENGINES USING PRODUCER OR NATURAL GAS AND DIRECTLY CONNECTED TO 60-CYCLE GENERATOR (AUXILIARIES NOT ALLOWED FOR)

The range in weights of the various sizes of horizontal type producer-gas and natural-gas, four-cycle single- and double-acting tandem and twin-tandem gas engines, as manufactured by the largest gas engine companies in this country, is shown in Fig. 7.

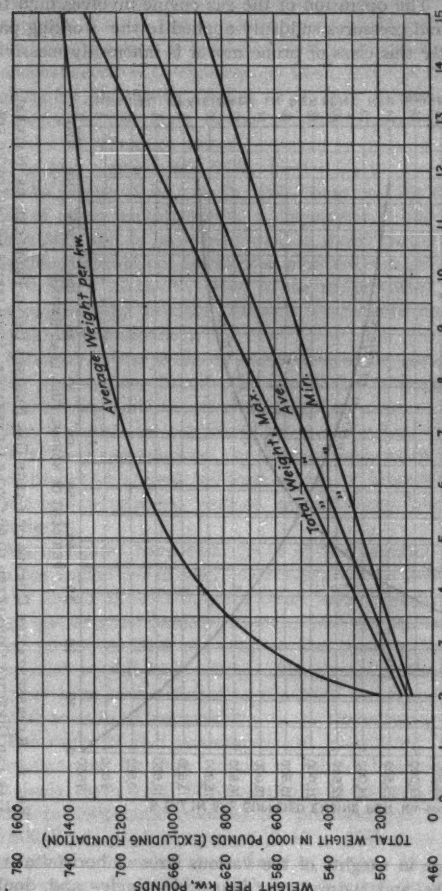

FIG. 7—HORIZONTAL TYPE (AMERICAN MANUFACTURE) PRODUCER GAS AND NATURAL GAS ENGINES, 4-CYCLE, TANDEM AND TWIN TANDEM, DIRECTLY CONNECTED TO 60-CYCLE GENERATORS FROM 200 TO 2000 KW. CAPACITY AT 80 PER CENT POWER FACTOR

These curves are drawn to include all capacities from 200 to 2000 kw., and show that there is a variation of 20 per cent from the average weight. Considering the curve of average weight per kilowatt, one thing is basic, namely, that the big unit weighs more per kilowatt than the small unit. The reason is that as you go up in size and lengthen out the stroke the weight runs up per unit capacity. The weight is governed by many considerations, such as rotative speed, the mean effective pressure on which the builder figures his rating, the nearest size the builder has to fit a given generator, the question of single or double crank, etc.

Cost. On account of the heavy parts made necessary by high temperatures and pressures, the gas engine is considerably more expensive to build than steam turbines or steam engines.

In some types of gas engines there is not very much difference between the cost per unit capacity in large and small sizes, whereas with other companies it varies considerably.

Fig. 8 shows the limits of total cost, average cost per kilowatt capacity, and average cost per pound, of the type and size of engine and generator as described in Fig. 7. The price is for engine and generator complete and installed, exclusive of foundations, within 600 miles of factory. It will be seen that the price varies 18 per cent from the average for the different types.

The cost of the gas engine is influenced by the same conditions that govern the weight, as explained above. The different combinations of stroke and synchronous speed result in varying piston speeds, and for a given power the price will be higher the lower the speed. Many attempts have been made to lower the cost of the gas engine by decreasing its weight without impairing its reliability, and to increase its capacity by increasing the pressure of the charge and simultaneous scavenging of the exhaust gases, but all without definite results.

Oil Engines

Oil engines have progressed rather slowly in this country, while in Europe the development has been more marked, especially since the expiration of the basic Diesel patents in 1912.

The Diesel engine is essentially a vertical type, but the last two years have witnessed a remarkable development of the horizontal type. While tests show that the fuel consumption is slightly higher than with the vertical type, nevertheless on account of the greater simplicity and better accessibility and

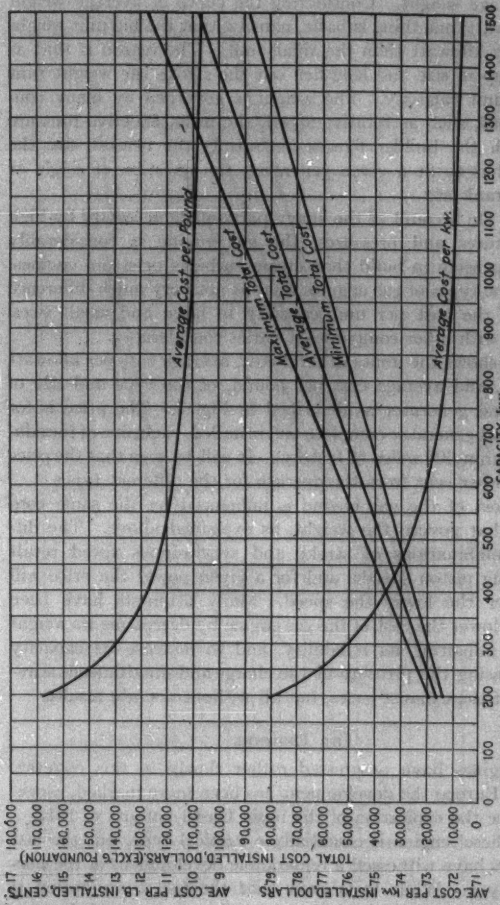

FIG. 8—HORIZONTAL TYPE (AMERICAN MANUFACTURE) PRODUCER GAS AND NATURAL GAS ENGINES, 4-CYCLE, TANDEM AND TWIN TANDEM, DIRECTLY CONNECTED TO 60-CYCLE GENERATORS FROM 200 TO 2000 KW. CAPACITY AT 80 PER CENT POWER FACTOR

lower cost, many manufacturers have launched out to build them.

There are approximately 300 installations of medium- and heavy-duty oil engines, aggregating over 75,000 h.p., in operation in the United States.

On account of the very high cost of natural oils in countries that do not have an oil production of their own, the use of tar oil with a small addition of ignition oil in the Diesel engine is rapidly finding favor. Some oil engines operate satisfactorily on any fuel and especially the crude oils produced in this country, while others are limited to certain qualities. The recognition that coal is too valuable a fuel to be wasted in our present-day furnaces, is spreading, and much interest is being taken in the by-product coke oven and by-product gas producer plants, in hope that the production of tar oil, an artificial product, will aid to check the advance in price of natural liquid fuels. In this country the condition is different on account of the supply of rich natural oils, such as the light grades of crude oil produced in the eastern fields, as well as the heaviest grades produced by the California, Texas, Oklahoma and Mexican fields, which are largely asphalt base.

Capacity. Similar to the gas engine, the oil engine does not possess an inherent overload capacity in the same sense that the steam turbine does, hence, whatever overload is required must be provided by the manufacturer.

The oil engine is restricted in size for the same reasons given in the case of gas engines. The largest Diesel engine operating in this country is a 450 brake horse power double-unit vertical four-cycle three-cylinder type, whereas in Europe they have been built as large as 2500 brake horse power. There has recently been built in Germany a 2000 brake horse power horizontal double-acting, four-cycle, twin-tandem Diesel engine operating with tar oil, which promises interesting results.

Efficiency. The thermal efficiency of the oil engine varies slightly with the capacity. Unlike the gas engine, the thermal efficiency does not increase with the load beyond the capacity of the engine.

Figures of efficiency have been given at different times that cannot be substantiated. With oil having 19,000 B.t.u.'s (4788 large calories) per lb. (0.4534 kg.), the thermal efficiency and fuel consumption that may be expected at different percentages of normal full load rating, no allowance being made for auxiliaries, are shown in Fig. 9.

At full load the fuel consumption is 0.64 lb. (0.29 kg.) per kw-hr. or 0.45 lb. (0.204 kg.) per brake horse power, and the thermal efficiency 28.2 per cent per kw-hr., or 29.8 per cent per brake horse power.

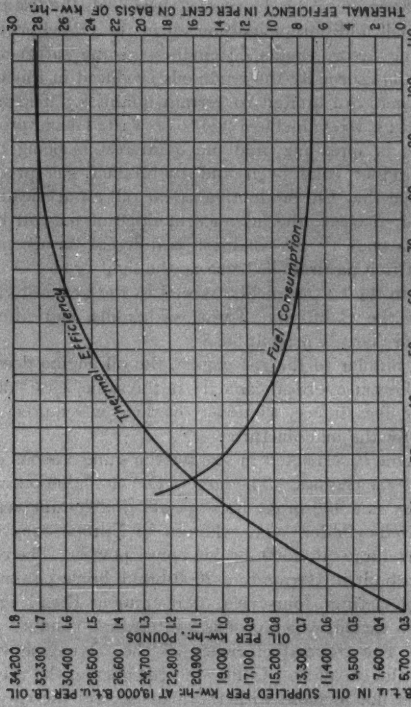

FIG. 9—VERTICAL DIESEL ENGINE, 4-CYCLE, 3 AND 6 CYLINDERS, DIRECTLY CONNECTED TO 60-CYCLE GENERATORS (AUXILIARIES NOT ALLOWED FOR)

The fuel consumption of the best oil engines to-day, made in large sizes, varies from 0.40 to 0.50 lb. per brake horse power, the highest fuel economy being obtained by the four-cycle type.

Weight. The Diesel engine is inherently massive for the same reason as the gas engine, namely, high temperatures and

pressures, consequently the weight, including engine and generator, per kilowatt capacity, increases with the size, as shown in Fig. 10.

It will be seen that the increase in weight from 40 to 160 kw. capacity is very rapid, while with sizes larger than 160 kw. it is not so pronounced.

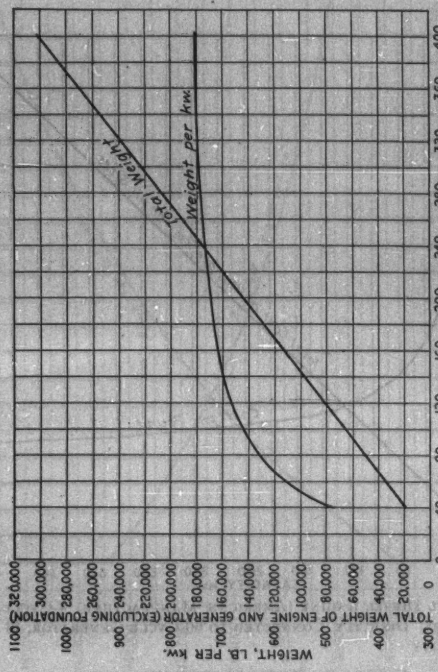

FIG. 10—VERTICAL DIESEL ENGINE (AMERICAN MANUFACTURE), 4-CYCLE, 3 AND 6 CYLINDERS, DIRECTLY CONNECTED TO 60-CYCLE GENERATOR, 40 TO 400 KW. CAPACITY.

High-compression Diesel-cycle crude-oil engines of the two- and four-cycle, single- and twin-cylinder, horizontal type, using a heavy grade of crude oil, are now being manufactured in America as large as 500 h.p. capacity, some companies standing ready to construct units of 800 h. p. capacity if required. Fig. 12 shows the average total weight and weight per kilowatt capacity for these machines.

Cost. There have been so few oil engines driving generators of any appreciable size installed in this country that it is a difficult matter to tabulate any costs for comparative purposes with other prime movers. The most reliable figures available for the Diesel engine average approximately $95 per kilowatt installed, including engine and generator complete, but not the foundations, within 600 miles of factory. Fig. 11 gives the

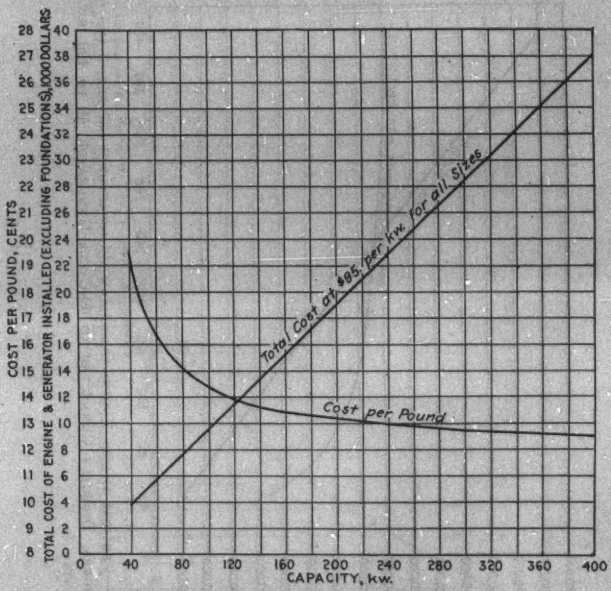

FIG. 11—VERTICAL DIESEL ENGINE (AMERICAN MANUFACTURE) 4-CYCLE, 3 AND 6 CYLINDERS, DIRECTLY CONNECTED TO 60-CYCLE GENERATOR, 40 TO 400 KW. CAPACITY

average total cost per kilowatt for all sizes at $95 per kw., also the cost per pound, which decreases but slightly for machines above 160 kw. capacity.

Important improvements in the construction of the vertical type Diesel engine are being made in this country, as well as in Europe, which will probably reduce the weight and consequently the unit cost.

The average total cost, average cost per kilowatt and average cost per pound of two- and four-cycle, horizontal, crude-oil engines, American manufacture, including engine and generator,

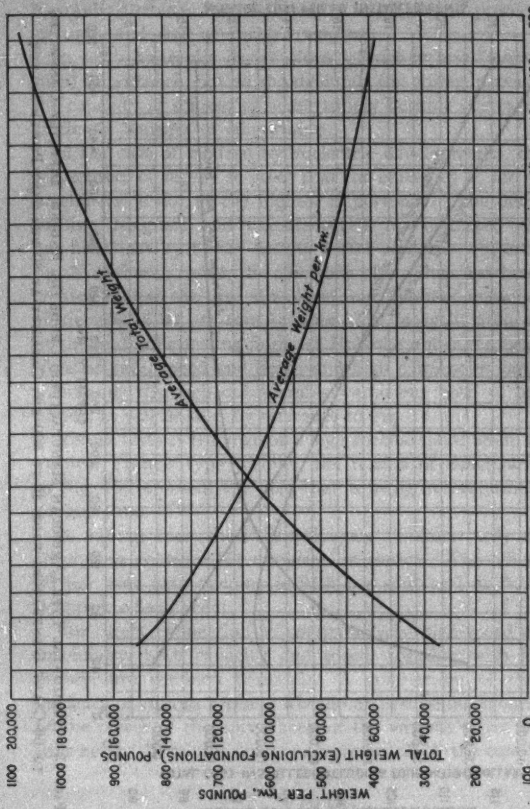

FIG. 12—HORIZONTAL TYPE (AMERICAN MANUFACTURE) CRUDE OIL ENGINE, DIRECTLY CONNECTED TO 60-CYCLE GENERATORS FROM 40 TO 500 KW. CAPACITY AT 80 PER CENT POWER FACTOR

are shown in Fig. 13, corresponding to the weights given in Fig. 12.

There is considerable variation in the weights and costs of the horizontal type oil engines of the different manufacturers,

and for this reason the average curve is given instead of the maximum and minimum. The weights and costs are fairly consistent for the single cylinders of all sizes, the greatest difference being with the twin- and four-cylinder types. These curves hold fairly well for the so-called semi-Diesel horizontal type.

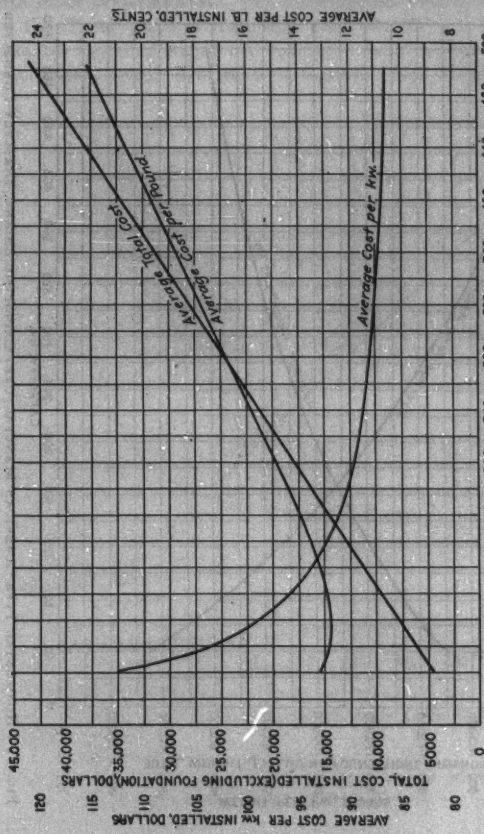

FIG. 13—HORIZONTAL TYPE (AMERICAN MANUFACTURE) CRUDE OIL ENGINE, DIRECTLY CONNECTED TO 60-CYCLE GENERATORS FROM 40 TO 500 KW. CAPACITY AT 80 PER CENT POWER FACTOR

Hydraulic Turbines

The development of hydroelectric power installations has created new demands on the designers and manufacturers of hydraulic turbines for betterments in efficiency, power, speed, strength and size of turbine runners.

In early hydraulic installations, efficiency was frequently of small importance, but as the demands for power increased, and the capacity of sources of water supply became overtaxed, high efficiency became of importance.

In the case of modern hydroelectric developments, there are few sources of supply so great that the efficiency of the installed machinery is not of the highest importance. The demand on turbine designers and manufacturers for increased efficiency has been met by better design, better construction, and better finish; and as a result, the efficiency of turbines has been so increased that in the case of at least four different manufacturers, efficiencies of 90 per cent or over have recently been obtained at the hydraulic testing flume at Holyoke under the best conditions of gate, speed and head; and high efficiencies can now be maintained through considerable variations both of head and power, as will be seen by reference to Fig. 14.

Recent tests at Holyoke on a high specific speed 28-in. (71-cm.) vertical Francis type turbine, the results of which are shown in Fig. 15, represent the best that is being accomplished at the present time.

It will be seen that the efficiency remains fairly constant through a considerable variation in power. The efficiency at 90 per cent gate opening is 91.5 per cent and at full gate it dropped to 84 per cent.

For direct connection to comparatively high-speed electrical machinery, both capacity and speed, together with high efficiency, are common demands. A comparison of the power capacity of various types of wheels can best be made on the basis of the power of the unit wheels of the various types under the unit head. This unit power is represented by the equation

$$\mathcal{P} = \frac{P}{D^2 h^{3/2}}$$

$\mathcal{P}$ is the unit power of the unit wheel of the type considered under unit head,

P is the power (h.p.) of any wheel under the head h,

D is the diameter in inches of the wheel considered,

h is the head in feet under which the power (P) is developed.

In each case the best conditions of speed and efficiency are assumed to obtain.

In the original Boyden-Fourneyron turbine of 1849, the value of φ was equal to..... 0.00032

This was increased by Swain in 1855 to.... 0.0008

By McCormick in 1860 to..... 0.0014

By a number of recent designers to values from 0.002 to 0.0024

And has been extended to..... 0.00388

in a recent design, without a reduction in efficiency below 87 per cent, an enormous increase in power which is quite worthy of note.

Capacity and speed are both often highly desirable for electric machinery if both can be extended without too great a sacrifice in efficiency. The combined capacity and speed may be compared by the speed-power coefficients of the various types (see page 1409, Vol. XXXI, TRANSACTIONS A. I. E. E.), which may be termed the "specific power" of the wheel, and which is represented by the equation

$$\varphi_s = \frac{n^2 P}{h^{5/2}}$$

in which n = the revolutions per minute of the wheel under the head h and with the horse power P. The speed-power coefficient φ_s is the square of the coefficient of unity speed.

The value φ_s = 10,000 had barely been reached in 1910, but during the present year a designer has succeeded in increasing the value to φ_s = 11,800.

Such wheels are frequently of high value for low-head and high-speed conditions, but cannot maintain such high efficiencies under great ranges of head and loads as can be maintained with wheels of lower "specific power," such as are shown in Fig. 14.

Among the more recent improvements in the construction of hydraulic reaction turbine runners may be mentioned the construction of high-capacity runners of cast steel in single castings, thus giving great strength with large capacity under high heads to which such turbines could not previously be applied.

The recent successful construction of the large single reaction turbines for the Keokuk hydroelectric plant is also worthy of note. These turbines are 16 ft. 2 in. (4.875 m.) in diameter and will operate at 57.7 revolutions per minute under a 32-ft. (9.75-m.) head. The runners weigh 73 tons each and develop 10,000 h.p. While greater power has previously been developed by single wheels

under high heads, these wheels are remarkable for the amount of power developed under the low head utilized.

Since 1911, the trend has been toward the adoption of the single-runner, vertical-shaft turbine for low and medium heads. This change in type of unit is due to the recent progress in the

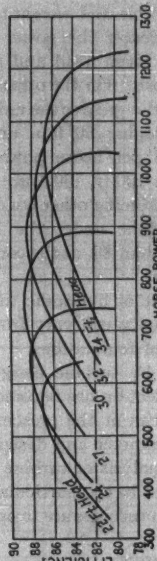

Fig. 14—Waterwheels

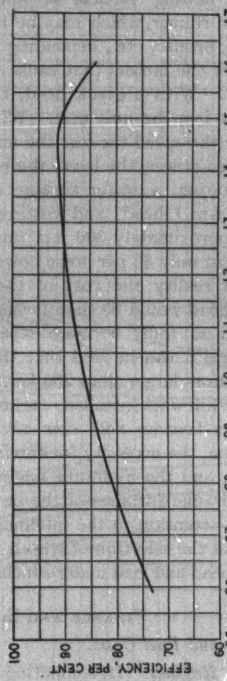

Fig. 15—Efficiency Curve of High-Speed Vertical Francis Type Turbine

design and development of high-capacity runners, also the improvement in thrust bearings.

Prior to this time, the majority of turbines for low and medium heads were either of the vertical-shaft, multi-runner type, or of the horizontal-shaft, multi-runner type.

Weight and Cost. The weights and costs of hydraulic prime movers are not strictly comparable with the steam turbine, gas

and oil engines, for in the case of the thermodynamic prime movers, the conditions are more or less fixed and the costs relatively uniform, whereas with the water turbines they vary between fairly wide limits, depending upon the conditions under which they are to be operated. The head, kind of flume, open or closed, setting vertical or horizontal, single or multiple, material in runner, which may be made of cast iron, cast steel, gun metal, bronze, etc., depending upon the service conditions, are some of the factors that cause the price and weight to vary materially. With a given head, the greater the power of the turbine the less the unit cost. With a given head and power, the higher the speed the less the unit cost. On the other hand, with a given power, the lower the head the greater the unit cost. For illustration, a water turbine developing 50 h.p. under a 30-ft. (9.14-m.) head, and costing $18 per horse power, will develop approximately 300 h.p. under a 100-ft. (30.4-m.) head, and will cost only $3 per horse power, assuming other conditions equal. In reality the cost of the turbine under the 100-ft. (9.14 m.) head would be slightly higher than $3, as the construction would naturally be more expensive.

In general it can be said that the cost of hydraulic turbines and generators larger than 200 kw. capacity will vary from $30 to $10 per kilowatt installed, exclusive of foundations.

With the broader field now covered by turbine design and construction, the necessity for careful selection has become most important, and the hydraulic engineer can at the present time secure hydraulic turbines of the best character and design only by careful attention to the intelligent analysis of turbine possibilities, and the selection of wheels suited to the particular conditions of head and load under which such turbines are to operate.

Finance and Economics

Investment and Fuel Costs.

a. Heat Engines. In comparing the various types of prime movers, conclusions are often reached, largely from a study of the cost of fuel, without any reference whatever to the total cost of power and the relative investment costs. As it is not within the scope of this paper to include operating and maintenance costs for the entire plant, investment costs of the units and fuel costs are shown plotted in conjunction with the percentage of normal full-load rating in Figs. 16 and 17, for making an economic study of the various types of prime movers.

The impression that gas and oil power invariably imply a lower cost of generation is constantly losing ground through the critical analysis of the elements of power costs. Fuel is

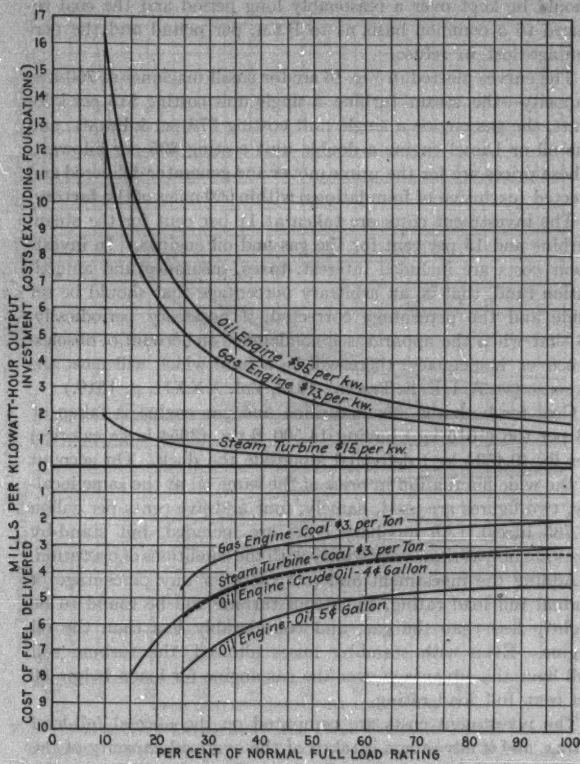

FIG. 16—RELATIVE INVESTMENT AND FUEL COSTS OF A 750-KW. STEAM TURBINE, GAS ENGINE, AND OIL ENGINE, INCLUDING DIRECT-CONNECTED 60-CYCLE-GENERATOR, OPERATING AT DIFFERENT PERCENTAGES OF NORMAL FULL LOAD

only a fraction of the total cost of power, and there are conditions where it is overbalanced by other costs.

Claims have been repeatedly made that steam turbines use

two and one-half times the amount of fuel consumed by gas engines, but these statements are without foundation. Before any fair comparison can be made of fuel consumptions, records should be kept over a reasonably long period and the coal reduced to a common basis as to B.t.u. per pound and the percentage lost in refuse.

The curves plotted in Fig. 16 are for small machines of 750-kw. capacity—the steam turbine a single unit costing $15 per kilowatt, the gas engine a single unit costing $73 per kilowatt, and the oil or Diesel engine a double unit costing $95 per kilowatt. These prices are for the prime mover and generator delivered and erected (exclusive of foundations) within 600 miles of the factory.

The investment costs are taken at 11 per cent for the steam turbine and 15 per cent for the gas and oil engines. In investment costs are included interest, taxes, insurance and amortization fund, that is, an arbitrary percentage that should be set aside and the percentage corrected, if necessary periodically, so that when the apparatus is condemned on account of obsolescence or inadequacy, there will be a fund which will meet the expense (see A. I. E. E. TRANS., 1913, Vol. XXXII, p. 1619.)

Coal for both the steam turbine and gas engine is taken at $3 per ton (1016 kg.) having 14,500 B.t.u. (3654 large calories) per lb. (0.4534 kg.) delivered alongside the dock. On account of the wide fluctuation in price of the same oil at the same locality, two figures are used, namely, four and five cents per gallon (3.785 litres). All auxiliary costs are included, but stand-by costs are not, as these vary widely with the conditions of operation.

Adding the investment and fuel costs for any percentage of normal full load rating, the steam turbine will be found to be slightly less than the gas, and considerably less than the oil engine. Even with stand-by losses allowed, the turbine will still have the advantage over the gas engine for loads below 80 per cent full load rating.

The investment costs are computed on the normal full-load rating, and if advantage is taken of the overload capacity of the turbine, which is approximately 25 per cent for 24 hours, the cost per kilowatt-hour during such periods of maximum capacity will be less than shown by the curve. This does not apply to gas and oil engines, as what little overload capacity may be allowed in these machines is for a short period of two hours or even less.

Another set of curves is plotted in Fig. 17, showing a single turbine unit of 20,000-kw. capacity, costing $7.50 per kilowatt, ten 2000-kw. gas-engine units costing $65 per kilowatt, and

forty 500-kw. oil-engine units at $85 per kilowatt. In a plant of this capacity the gas and oil engines are practically out of the running, with these fuel costs.

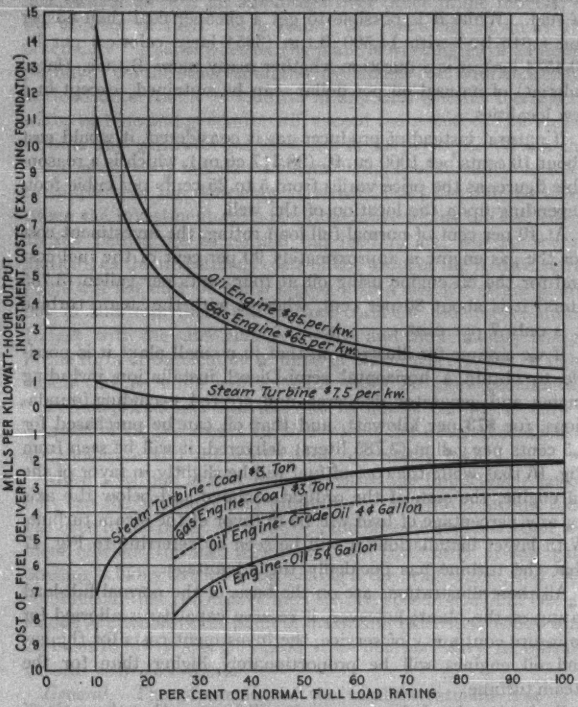

FIG. 17—RELATIVE INVESTMENT AND FUEL COSTS OF PRIME MOVERS DIRECTLY CONNECTED TO 60-CYCLE GENERATORS OF 20,000 KW. CAPACITY, OPERATING AT DIFFERENT LOADS

Steam Turbine—1 unit 20,000-kw. normal rating.
Gas Engine—10 units 2000-kw. " "
Oil Engine—40 units 500-kw. " "

In computing the cost of fuel the coal was put on the same basis, namely, 10,825,000 B.t.u. (2,727,868 large calories) per dollar, whereas the oil at 4 cents per gallon is equivalent to

3,718,000 B.t.u. (936,925 large calories) per dollar. This may look as though the steam turbine and gas engine were being favored, but in comparing prime movers as they stand to-day they must be considered in connection with the prevailing cost of fuel. While it is possible to get a cheaper coal than $3 per ton (1016 kg.) with 14,500 B.t.u. (3654 large calories) per lb. (0.4534 kg.), it is a question whether many more B.t.u's. (large calories) of natural oil per dollar can be obtained, except in a few localities.

If natural instead of producer gas is considered, it would cost about 10 cents per 1000 cu. ft. (28.317 cu.m.), which is a reasonable figure, as the price varies from 5 to 25 cents per cubic foot, depending upon the location of the well.

At 40 per cent of normal full-load rating, the investment cost for the gas engine is approximately 90 per cent of the fuel cost and for the oil engine using oil at four cents per gallon (3.785 liters) it is about 80 per cent, whereas with the steam turbine it is only 7 per cent.

If we assume for illustration, that in a small plant it is possible to obtain a horizontal semi-Diesel installation, including engine and generator delivered and erected, excluding foundations, for $73 per kilowatt, and that oil can be purchased for 3.5 cents per gallon (3.785 liters) delivered, it will be seen from Fig. 16 that while the cost of fuel will be slightly in favor of the oil engine, the sum of the ordinates above and below the axis for any percentage of load will be in favor of the steam turbine. With larger installations it will be seen by referring to Fig. 17 that the turbine has decidedly the advantage.

All these illustrations are on the basis of the normal full-load rating of the plant; however, if reserve capacity is allowed for to insure continuity of service, the investment costs for the gas and oil engines will be proportionately higher than for the steam turbine.

From a study of these curves it will be seen that the ratio of cost of steam to gas and oil units is decidedly in favor of the former so that gas and oil power becomes severely handicapped in large work owing to the proportionately greater investment burden. And, unless the price of coal rises materially above the present value, the gas and oil engines will find limited application in stations of any appreciable size, except under very favorable circumstances, where natural gas, by-product gas or some artificial fuel oil can be secured at low prices. If maintenance cost and the additional investment cost required to assure re-

liability or continuity of service are included, the steam turbine will stand out more prominently.

b. Hydraulic Turbines. The redeeming feature of the water turbine, which gives it an advantage over other prime movers, is the absence of fuel. As a result, the operating expenses are practically the same whether the plant is working 10 or 24 hours per day. On the other hand, the investment cost is influenced by the load factor, but it is doubtful in any case whether the cost of water turbine and generator will exceed twice that of the steam turbine and generator on the basis of 11 per cent. When the investments costs include an adequate supply of auxiliary capacity to supplement the deficiency in stream flow, the difference between the investment costs of prime movers plus the fuel costs, at any percentage of normal full load rating, will not be so marked, as the investment costs of the units of the hydroelectric plant will not only be much higher than a straight steam plant, but in addition, there will be fuel costs for the reserve units. In fact, with the same class of service, and the reliability charge in the form of duplication of units or steam reserve, the straight steam turbine units will in many cases be more economical.

In low-priced fuel districts the hydraulic turbine is only a competitor of the steam turbine where the development costs are moderate and the load factor reasonably high.

More attention is now being given to the important relation between the efficiency and durability of the water turbine than has been in the past. It is the opinion of some engineers that the most efficient turbine, if operated too constantly at low gate opening is likely to show some pitting if the head is high, and they recommend that turbines of high specific speed be kept as closely loaded as possible to the point of maximum efficiency, while with turbines of lower specific speed it is not necessary to operate within such close limits.

General. The proportion of the total investment cost of a 20,000-kw. plant represented by the prime mover and generator for the various types of units, is approximately as follows:

Prime mover	Total investment cost per kw.	Cost of prime mover and generator per kw.	Percentage of total investment
Steam turbine.....	65.00	7.50	11.5
Gas engine..... (Producer gas)	140.00	65.00	46.5
Oil engine.....	120.00	85.00	71
Hydraulic turbine ..	125.00	12.00	9.6

The unit costs are the average values obtained from the cost curves given above, while the total costs were estimated and are only approximate, especially in the case of the oil engine, as it is impossible to obtain reliable data for this type of installation.

Considering the different types of prime movers in connection with the total investment cost of the plant, it is evident from a study of curves similar to Figs. 16 and 17, developed on a load factor and total cost basis, that with a very poor load factor the all-important point is to keep down the fixed charges, as they are of vastly greater importance than any possible gain in efficiency due to a better type of prime mover of the same class. This is true of any plant, and the curves will show the futility of attempting to carry peak loads by means of water turbines, gas

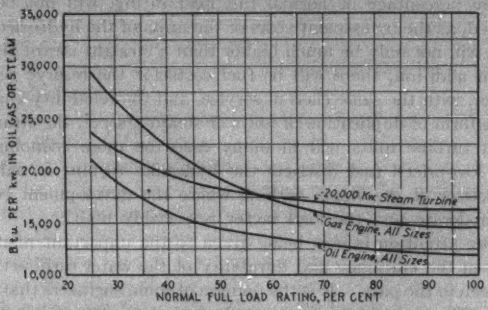

FIG. 18—RATES OF HEAT CONSUMPTION PER KW. AT DIFFERENT PERCENTAGES OF NORMAL FULL-LOAD RATING

and oil engines or any prime mover that necessitates a large investment per kilowatt.

Efficiency and Heat Consumption. Figs. 18 and 19 are presented to show conservative thermal efficiencies and heat consumptions in B.t.u. per kilowatt-hour at different percentages of normal full-load rating, for two sizes of steam turbines and for all sizes of gas and oil engines, reckoned on the heat in the steam, gas or oil delivered to the throttle valve, and do not include boiler or producer losses or auxiliaries.

It is evident that as the larger sizes are approached the inequality between the steam turbine and gas engine steadily vanishes until finally the former exceeds the latter. It is interesting to note that at normal full-load rating the thermal efficiency of

the 20,000-kw. steam turbine, which is based on 175 lb. steam pressure and 100 deg. superheat, is 24.2 per cent, and the producer or natural gas engine 23.8 per cent, both referred to kilowatt-hour output. Referring to Fig. 2, it will be seen that the average thermal efficiency of steam turbines larger than 14,000 kw. is between 24 and 25 per cent, and the maximum value for very large machines is a little below 25.5 per cent.

An important feature of the steam turbine, and especially the oil engine, is that the efficiency does not materially decrease

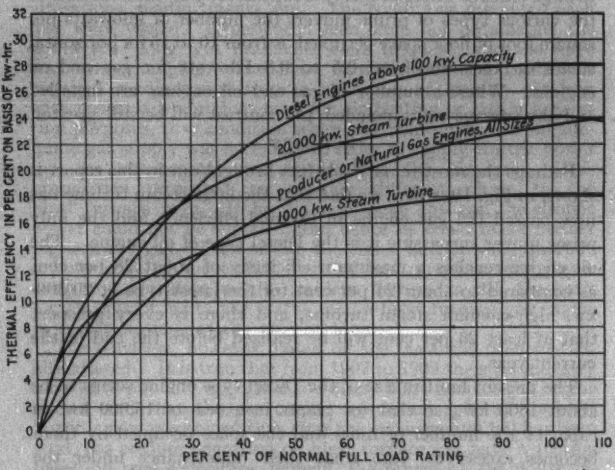

FIG. 19—THERMAL EFFICIENCY OF PRIME MOVERS (AUXILIARIES NOT ALLOWED FOR)

until the load falls below 25 per cent of the normal rating, whereas the gas engine changes rapidly.

In small plants with a low load factor, efficiency may be a secondary matter compared with investment cost, and the cost of maintenance and reliability.

Maintenance and Reliability. On account of the high mechanical stresses inherent in the gas and oil engines, and heavy reciprocating masses, there is necessarily greater maintenance and repair cost, also a lower reliability of ser-

vice and a higher class of attendance than for either the steam or water turbine units. The reliability of the gas and oil units has not been sufficiently established to warrant their adoption for reasonably large power stations operating 24 hours daily, without the plant being over-burdened with some type of reserve and consequently excessive investment costs.

Space Economy

This factor affects the investment cost of power, and is especially of very great importance for plants of any appreciable size in large cities or where property is expensive. For different sizes of the various types of prime movers the number of kilowatts per square foot of floor space occupied, is from 10 to 15 for horizontal steam turbines, and from 0.5 to 0.8 kilowatt for gas and oil engines. Where a number of gas and oil engines are installed and the passage-ways included, the contrast will be still greater.

Summary

Perhaps the most remarkable fact brought out in this report is shown in Fig. 19, where we find that the large steam turbine has now passed the gas engine in thermal efficiency and the only prime mover surpassing it is the Diesel type of oil engine. The oil engine reaches a maximum efficiency of about 28 per cent as compared to about 24 per cent for the latest type of 20,000-kw. high-vacuum steam turbine, and there is every prospect that at least 26 per cent will be realized before the end of the current year.

The present limit in size of the Diesel type engine seems to be about 1800 kw., so that for plants in excess of 15,000 kw. in capacity the number of units and the space occupied by them becomes excessive. Just what their maintenance under the high cylinder temperature will be is dubious, as there are not sufficient data available to enable the Committee to report.

Figs. 16 and 17 summarize the whole prime mover situation in the combined curves of investment and fuel costs, as by taking the sum of the ordinates at any percentage of the rated load it will be seen that the steam turbine is far more economical than any other type of heat engine.

In conclusion the authors wish to acknowledge their indebtedness to Mr. D. W. Mead, a member of this committee, for the curves of Fig. 14 and a portion of the section on hydraulic turbines, and also the kindness of a number of manufacturing companies in furnishing the necessary data.

DISCUSSION ON "PRESENT STATUS OF PRIME MOVERS" (STOTT, PIGOTT AND GORSUCH), DETROIT, MICH., JUNE 25, 1914.

R. Tschentscher: The division entitled "Gas Engines" comprises internal combustion prime movers using natural gas, producer gas, or blast furnace and coke oven gas. The relative measure in which each enters into the problem is not given.

In 1907, blast furnace gas engine installations began in the iron and steel industry. It was my lot at that time to place in service and operate the first plant of any considerable size. Power from the plant referred to was imperative, and there was therefore but little time for miscellaneous experiments, alterations, readjustments, etc. The conditions presented each day were varied. Experienced men were not obtainable, the hours were long, gas headaches were frequent, and the force was ever changing. The blast furnace operating conditions required readjustment from a condition of making pig iron with gas as a by-product used for air heating or steam generation purposes, to a condition where the maintenance of an adequate gas supply was necessary in order to supply electric power for the equipment used in making the pig iron. This proposition presented an entirely different phase to the blast furnace man. If he did not make the gas, the electric power could not be supplied, and hence he could make neither pig iron nor gas. I am afraid, therefore, that in some quarters a knowledge of the earlier more or less unsatisfactory power costs and operating results incident thereto, is still the basis for an opinion as to the status of the blast furnace gas engine in power stations at the present time.

The situation, however, based on the facts has been materially altered. It is true that from 1907 to 1909 the steel industry may have put into operation too many blast furnace gas engine plants, and that the gas engine reputation suffered thereby; but it is now recognized that after the experimental bill has been paid, gas engines operating on blast furnace gas have a footing based on true economics, namely, the return on the dollar invested, all factors considered.

At the present time statistics which I endeavored to collect show that there is approximately 450,000 kw. generating capacity in the steel plants that sent returns to me. Of that capacity, approximately 175,000 kw. use gas engine generation. The United States Steel Corporation alone has installed and in service approximately 140,000 kw. of gas engines operating from blast furnace gas. The various sizes of the plants range from 1000 kw. to 64,000 kw. in one plant.

About a year ago a paper was read before the Iron and Steel Institute, in which were given blast furnace gas electric power station costs, not including investment costs or other fixed charges, that were, approximately, $2.75 per 1000 kw-hr., being 2.7 mills per kw-hr. These figures were the results of a year's

operation, 1912, I believe. These figures covered the operation of units, most of which were of the earlier type. Since that time the situation has materially changed. A 2000-kw. unit is not the limit of size by any means. Manufacturers are prepared to build now, and have had in operation for some time, units of 3000 kw. The exact weights I do not recall, but the weight per kilowatt for the 3000-kw. unit is much lower than it is for the 2000-kw. size. The operating costs for a plant composed of 3000-kw. units, as now manufactured and as operated for at least two and a half years, are lower than 2.7 mills.

J. R. Bibbins: Does that include the investment?

R. Tschentscher: No, the figures do not include investment. They are what is customarily considered as power station cost.

I wish to comment on a few specific points mentioned in the paper. In Fig. 16 are given fuel costs for a 750-kw. unit. For fear these may be taken as representative of what the gas engine can do, I will say that from my knowledge of the subject it appears to me to be not equitable to compare the 750-kw. unit with the turbine or reciprocating engine of that capacity. I am discussing this subject merely from the standpoint of blast furnace gas engines, not natural gas or producer gas engines. A steel plant requiring but 750 kw. would far better install a steam power prime mover or buy its power from some other source, because such a plant will probably have considerable periods in which there will be no gas available and no furnace in operation, and hence no power can be generated from the gas engine installation. I think it may be stated as a fact that the 750-kw. gas engine has no place in the steel plant. Therefore, comparison by using such units, as far as the blast furnace gas engine is concerned, may be misleading.

On the page following Fig. 16, the cost of $3 per ton is used as the cost for fuel in the relative comparisons, which, I believe, is too high when considering cost of fuel as used by steel plants. Most steel plants are located at a point of low fuel cost, and $2 would more nearly represent the true condition.

In the last paragraph of that page it is stated that the steam turbine has an overload capacity of approximately 25 per cent for 24 hours, while the gas engine is credited with an overload capacity for short periods, two hours or even less. That may apply very well to the motive power end of the unit. A steam turbine, no doubt, can operate for 24 hours a day at 25 per cent overload. To a large extent the gas engine may or may not be able to do that, depending on the design, depending on how free the manufacturer was in his guarantee. However, as far as the generator is concerned, I cannot see why the generator on the gas engine cannot have the same overload capacity for the same length of time as that of the turbine or the steam engine, provided they are built on the same standards.

Fig. 17 refers to some interesting data, namely, the cost of 20,000-kw. steam turbine units. I presume that what was in-

tended here was a comparison of the motive power end, the prime mover end, of a plant having 20,000-kw. capacity. If that is the case, it does not appear to me to be fair to allow one 20,000-kw. turbine as the capacity of a 20,000-kw. station. No one, of course, would so design it. It would be designed with two 20,000-kw., or three 10,000-kw., or four 7500-kw., or perhaps two 15,000-kw. units, depending on the overload capacity, in case one unit is shut down. The reason I mention that is this—the 20,000-kw. turbine is compared with ten 2000-kw. gas engines. Ten 2000-kw. gas engines such as may now be purchased, I believe will have a greater yearly kilowatt output than one 20,000-kw. turbine unit. Therefore, it appears to me that a much fairer comparison would be to arrange the curves to refer to a 20,000-kw. output station, each prime mover being of the most suitable size. This might, in the case of the gas engine plant, consist safely of eight 3000-kw. blast furnace gas engines or perhaps seven. I will not attempt to say how many oil engines, as I am not familiar with the subject. On this basis the situation is altered, and these curves will assume an entirely different shape. Eight 3000-kw. gas engines may be purchased for materially less than $65 per kw., installed on the foundations. Not having the figures definitely at hand, I am, however, of the opinion that $50 or less will purchase the equipment.

The table at the bottom of page 1163 deals with the total investment cost of gas engines and other prime movers, and I see it is stated that the cost of the producer gas engine is $140 per kw. Unless the price of producers has materially increased, I believe that is a high figure. When I first made my comments or notes here in connection with this particular table, I did not see that "producer gas" was put in parentheses. Some have the opinion that the blast furnace gas engine installation will run in the neighborhood of $140. It can be installed for materially less than that, not including, of course, land values, which vary so greatly, depending on location. Without considering land values, I believe a 30,000-kw. plant may be installed for from $85 to $100 per kw., including the gas cleaning plant, together with the necessary piping, all auxiliaries, etc.

On page 1165 the question of reliability is mentioned, giving the steam turbine by far the best of the argument. In that connection I wish again to say that the situation is materially different from what it was several years ago. The history of the operation of one particular plant for the past few years shows very reliable blast furnace gas engine operation—probably as reliable as a steam turbine plant, with the exception of, perhaps, a little unreliability in this local plant in the gas supply end, due to periodically restricted furnace operations. As far as the power station operation is concerned, modern gas engines are practically as reliable as steam turbines. It must be remembered that blast furnace gas engines operate twenty-four hours a day, because the mills operate on a twenty-four hours per day basis.

A paragraph on the last page of the paper deals with the question of space economy. It is stated that a gas engine installation requires twenty times the space of a horizontal steam turbine installation. When that figure was presented to me I pictured an 8000-kw. plant with which I am familiar and tried to figure whether I could replace that with a 160,000-kw. horizontal turbine outfit. I am perfectly safe in saying I could not. I could probably put a 70,000-or 80,000-kw. horizontal steam turbine plant in that space.

I would like to call the attention of any one who is interested in the subject of producer gas engines to the installation which the Ford Motor Company is now in process of making. There will be three 3750-kw. generators, direct-connected to twin tandem combined gas-steam engines, a very unique installation. What they will realize I do not know—one side of the outfit being steam-driven and the other producer-gas-driven; the boilers to be mounted above the producers, and the feed water to be heated from the waste gas of the gas engines. I understood in conversation this morning with one of the representatives of the company, that they have overcome the usual difficulties, and on that basis we are likely to see some exceedingly economical results obtained at that plant.

In conclusion, I would like to say that the paper which has been presented to us this afternoon is of very great value, but one is apt to draw erroneous conclusions from a paper which treats of prime movers only, and it ought to be emphasized that all these figures should be taken as representing prime movers only, and not as being typical of the entire generating plant. Operating conditions and costs of the boiler plant, the producer plant, or the gas cleaning plant, or similar factors relative to auxiliaries, may greatly modify the conclusions which may be drawn from a consideration of prime movers only.

J. R. Bibbins: This admirable paper brings forcibly to mind two fundamental facts both intimately related to the cost of power production: (a) the tremendously rapid increase in the capacity and the cost and weight efficiency of steam turbine units; (b) the correspondingly rapid aging of power generating apparatus by change in the art, and the heavy replacement or obsolescence charges resulting therefrom.

The one is evident on the face of the facts presented, the other, by experience only, and yet in an established property the burden of fixed charges due to obsolescence must be reckoned with and might operate to modify largely the relative economic positions of the various prime movers represented in this paper. It is to be hoped that the authors will present something further on this aspect of the question in the future.

While the general economic principles employed in this paper are quite unimpeachable, it seems to me that forced comparisons between the relatively small units of the internal combustion type and the large units of the steam turbine type can

hardly lead to conclusions fundamentally sound in the broader aspect of *system* vs. *size*. Thus the comparison drawn here for a 20,000-kw. plant is justifiable only in so far as it applies to the forced conditions of ten gas units vs. one steam unit. Obviously neither installation would receive serious consideration to-day as an effective layout, and a true comparison of systems should be made on smaller capacities. Thus in Fig. 18, the heat consumption curve of a 2000-kw. turbine would appear to much less advantage than that of the 20,000-kw. unit.

It is well that the authors have brought out the importance (page 1142) of the Rankine cycle as a detector of spurious water rates or heat consumption curves. I have in mind the case of a heat engine economy curve published some years ago as a wonderful performance. It looked rather "fishy," and I did not take even the trouble to work out the thermal efficiency, but simply applied the Willans law, as in Fig. 1. This very simple graphical method plainly showed that the heat consumption curve published was in error.

I am interested to know whether the net basis of heat units has been used in making these comparisons. Of course, either net or gross would not affect the *over-all* efficiency of a plant, at the coal pile, but it would most decidedly in the comparison of these thermal efficiencies. Also, approximately uniform gas engine piston speed was presumably used in making these comparisons of engines of various sizes. In the matter of the oil engine, while some of the auxiliaries might be dispensed with, I do not quite see how the air compressor can be disregarded. It is rather difficult to conceive of a Diesel type of engine without any auxiliaries, because the engine is absolutely dependent upon the air injection for its operation.

In Figs. 16 and 17 the authors have presented an argument that seems rather hard to combat, with two exceptions. One is the unfortunate choice in the size of units. Thus, in this comparison between the 20,000-kw. steam unit and the ten 2000-kw. gas units, it is important that these costs and economy curves should be correlated not only as to size, but as to method of operation. It should be assumed that the smaller units were put into operation consecutively. That is, 50 per cent plant rating should refer to *half load* on the 20,000-kw. machine, and half of the number of smaller machines running at *full load*, rather than half load on all of the small machines. I must confess that the latter method, here used, seems unduly unfavorable to the smaller units, because it is obviously possible, in an underloaded plant, to build up prime mover capacity to meet the load with far better over-all efficiency in small units than with one very large unit.

The other point is in regard to the price of steam or gas coal, $3 per ton. It was my pleasure to have quite intimate knowledge of the development of the bituminous producer in the use of low-grade fuels of various kinds. I have not followed very

recent developments, but in view of the success attained at that time it seems to me inequitable, except in certain individual locations, to assign to the producer gas plant as high a price for fuel as for steam coal. If the producer has any special field, it is as an apparatus designed for, and capable of, using low-grade fuels—for instance, the lignites in the West. Thus, any possibility of difference in the cost of coal (Fig. 16), would operate to overcome the higher investment cost assigned to the power gas plant.

Finally, there is one thought which occurred to me in this connection, especially as to the theory of prime movers, and their application, presumably, to central station work. In a previous paper, presented two days ago at this meeting, the question of special peak load apparatus came under discussion, and there occurred to me at that time, as many times before, the question whether the complete standardization of prime movers is absolutely essential in a plant only half of which may be called upon for peak load duty, and not for an hour necessarily, but perhaps for only ten or fifteen minutes. In street railway practise, for example, the maximum passenger movement occurs usually within ten minutes after 5:30 p.m. The reflex of this great volume of passenger movement on the power plant load does not by any means last over the hour.

Now, on the other hand, generators are universally rated upon at least an hour basis, and the question therefore arises, whether it would not be possible to develop a type of prime movers or combination of prime movers, of minimum cost, perhaps not quite as efficient (because the last grain of efficiency would not be necessary at the extreme peak), but of a type exceedingly sturdy in construction, one that could stand higher temperatures and excessive overloads for these short peak load periods. Of course, the steam turbine is able to do this now, though not designed *primarily* for peak load conditions. Perhaps a special combination of short peak ratings would suffice. It would be interesting to know how near power plant apparatus, as it is designed today, approaches the limit of ultimate capacity of materials used. It certainly is not impossible to determine this in the case of the gas engine installation, which, as you can see, is very seriously handicapped on the peak load basis.

H. M. Hobart: The authors give a table at the bottom of page 1163 in which the total investment cost per kilowatt is given. With the greatly decreased cost of steam turbines, the cost of the prime movers and the generators is now perhaps one-half, or even less, of the outlay for land and buildings in the case of a station located in or near a large city. It would be interesting if, in the first column of this table, the authors would indicate more precisely whether the total investment cost per kilowatt, at any rate in the case of steam turbine plants, includes a station to be laid down in or near a large city.

I want to call attention particularly to this matter of total

investment cost. I should be glad if the authors would qualify that figure of $65 for the total investment cost per kilowatt for the steam turbine plant, given in the table at the bottom of page 1163, with a precise statement of the allowance they have made for the land and buildings in the case they have in mind, since that is probably the largest component of all, and leaves us in a very vague frame of mind as to the composition of the total investment. Figures should preferably be given for each particular component of the total investment, and I should like to ask the authors to supply these component costs. It would be much appreciated if the authors would make a precise statement of the total cost in and near large cities, and also the corresponding allowance for land and buildings. This could be followed by the corresponding figures for the same size and design of station, but located exclusively with reference to an economical supply of coal and water and low prices for land. The addition of these data would be much appreciated.

E. D. Dreyfus: The admitted breadth of the subject of prime movers makes it possible only to treat of all of its phases but partially in a limited paper; however, sufficient has been presented to demonstrate that the steam turbine holds a superior position in view of the present prices of the different types of equipment and the existing fuel costs. Such an attitude regarding the equipment situation has been quite pronounced in the power industry during the past two or three years. As pointed out in the paper, the steam engine has for some time been rapidly losing ground. Greater use of the gas engine has been seriously checked by the lagging progress of the producer. While natural gas is an ideal fuel for the internal combustion engine, the available supply for power purposes is limited and therefore its price is too uncertain. Very little practical headway has been made in the utilization of the inferior grades of fuel such as peat, lignite and the low-grade coals.

While the gas engine has taken a prominent position in blast furnace and steel mill work, I do not believe it can fairly claim an undisputed title to that field. Possibly for a limited capacity it may show a small economic advantage. However, when the plant becomes of an important size the advantage in fuel economy not only vanishes, as illustrated in the paper, but the gas engine is exceedingly handicapped by its greater maintenance and attendance costs. For such reasons the gas engine will be unable to maintain its former popularity even among the steel men.

The writer made the statement about three years ago that the demand for gas engine plants would only be for installations of 1000 kw. or less, until there should be a material rise in the price of coal. Expected further developments in gas power equipment have also, no doubt, deterred the power plant owner from installing this type of equipment.

It might be well to illustrate by example the bearing the

item of labor has upon the total operating cost. The labor cost in a gas producer plant containing three 300-kw. units would be about $830 per month, while for a similar size steam turbine station it would be in the neighborhood of $570. For such small size plants the difference may not be serious, but on the other hand, if we were to compare plants say of three units

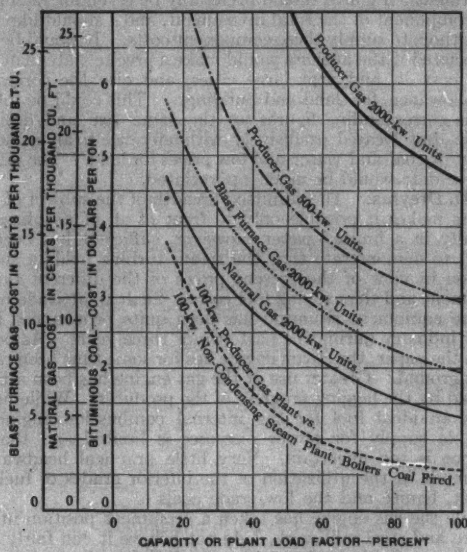

FIG. 1—PROPORTIONATE EQUALITY CURVES

Showing balance of total costs of generation in gas and steam plants with variable fuel prices and load factors.

Area above curves favors the gas engine; below, the steam turbine plants prove more economical. Based on general conditions in the text.

Fuel values

Bituminous coal	13,000 B.t.u.
Natural gas	975 B.t.u.
Blast furnace gas	80 B.t.u.

of 2000 kw. each, the gas engine station would involve a labor cost of about $3425, while the same capacity steam station would demand only $2020, roughly. If we take a plant of 20,000 kw., consisting, in the case of gas engines, of ten 2000-kw. units, and if steam turbines are used, of about four 5000-kw. units, the respective labor costs would be in the neigborhood of $11,180 and $4,475 per month. As the fuel economy of the gas

engine is but little better than the steam station when such sizes are considered, and, moreover, as the labor cost in the gas engine plant exceeds one-third the total operating expense, the internal combustion engine is obviously given a decided setback. This contrast has been made upon the basis of a 50 per cent load factor. The lower the load factor, the less economically will the operating force be applied, as a general proposition, so that labor cost will in a somewhat greater degree prejudice the gas engine plant at low load factors. It is rather difficult to show all the combination of factors at work to influence operating cost under the wide range of conditions that obtain.

I attempted to show, in a paper presented before the Association of Iron and Steel Electrical Engineers in 1911, the general relations of the different prime movers by taking into account all the elemental factors. As germane to the discussion, I am presenting (Fig. 1) one of the figures prepared at that time, which shows results obtained by taking into account all the different costs that enter into the power problem. Excepting the bottom curve, all the comparisons are between gas engine plants and steam turbine plants. The area above the curves favors the gas engine, and conversely, that below represents the economical field of the steam turbine. It will be observed that for large gas producer stations operating on low load factors, the cost of coal would have to be at some fabulous price to justify their existence. In the hydroelectric plant it is not only the absence of fuel that makes for low costs (assuming reasonable development cost), but the small operating and maintenance expense gives such a plant an excellent position when within close range of a favorable power market.

Referring to costs of oil engines, some recent figures obtained from a large American manufacturer indicated that the complete oil engine plant could be installed (including buildings and foundations) at costs ranging from $150 down to $100, depending upon the size of the plant. A representative of a foreign oil engine builder claimed that oil engines could be delivered and erected within reasonable shipping distance from port of entry, complete with building, at costs about 20 per cent below the figures just given. This is expecting a little too much, but the oil engine builders are working towards a reduction in the cost of the equipment, which should of course give this type of equipment a better competitive position. On the other hand, the lack of stability of oil prices has a disquieting effect upon the use of the oil engine. In the South and Southwest in the vicinity of the oil fields or in the neighborhood of the ports receiving Mexican crude, the oil engine increases in importance.

In any consideration of prime movers it is becoming better understood right along that we can not allow ourselves to be guided by technical conditions only. The human element enters seriously into a question of this kind. For a given

equipment the results obtained under actual operating conditions may differ in a marked degree, depending upon the ability and conscientiousness of the chief and his crew. This is more apparent in steam plants, as, with their liberal overload capacity, the output may be maintained though the efficiency may have fallen off greatly. With the producer gas engine plant, in the first place, a more competent force is required, and then if the force should become negligent the quality of the gas will suffer and at the same time no doubt there will result an inefficient mixture, so that the engine may fail to pull the load. Therefore, it may be said the gas engine will depart the least from its best operating efficiency. Another point—if the external load on the station is of a widely fluctuating character, the unit or "machine" load factor will be unfavorable, on account of the inadvisibility of operating without a conservative margin. In fact, if a gas engine is overloaded to any extent it is liable to fall out of step, and if the station comprises gas engines only, the effect becomes progressive and the whole plant will go down. I have observed complete shut-downs from just such causes. There are a great many operating considerations to be borne in mind, and this is unquestionably accountable for the marked inactivity of the gas engine business in the past few years.

H. G. Stott: Mr. Tschentscher is entirely mistaken in assuming that these comparisons refer to blast furnace gas practise, as that is specifically exempted. The blast furnace gas plant is not considered in the paper, excepting the reference on the page where we begin discussion of the gas engine, that is, on page 1142, where you will find due credit is given to the position of the large gas engines in steel plants, where we say, "The development of large gas engines is largely due to the ideal conditions existing in steel industries, where large quantities of blast furnace gas are available, requiring only cleaning to make a perfect fuel for this type of prime mover." Then we go on and refer to the fact that they have reached a capacity of 6000 brake h.p. for a single unit of the twin tandem type.

Now, some question was raised by Mr. Tschentscher and also by Mr. Bibbins, as to the comparison of costs of producing power, based upon the assumption of equal cost of fuel. I admit that possibly may be a little unfair, but how are you going to do it in any other way, in making comparisons? If we use cheaper fuel for the gas engine than we do for the steam turbine, there would be a complaint from the other side, because, as you know, in a great many cases, anthracite is used in producer gas engines, and anthracite is usually—not always—but in the larger sizes, is much more expensive than bituminous or semi-bituminous, so I think it is clear that for the purpose of comparison it was an impossibility for us to do anything but use the same price of fuel in both cases, because any needed correction can be made in this comparison. If, for example, you find the fuel to be used in the producer is 10 per cent or 50 per

cent cheaper, it is quite easy to make this correction in these curves. If we had started on an unequal assumption of price, it would have been very difficult to make the correction.

Mr. Bibbins asked about the kind of heat unit, whether gross or net heat unit. I do not understand the question, but I would say that we used the mean B. t. u., which is the average B.t.u. contained in steam between a temperature of 32 deg. and 212 deg., which is given in practically all the modern steam tables, which is 1/180 of the heat contained between two points, between 32 deg. and 212 deg.

There were a number of other questions raised, which I will be glad to answer further by a written discussion, as our time is limited now.

Of course, in making these comparisons it is obvious you must make generalizations. We have compared in one table here the results of all units; for example, in Fig. 16 we go up to a maximum size of 750-kw. units, but, in order to be perfectly fair to the larger prime mover, namely, the steam turbine, it is obvious we had to consider 20,000-kw. turbines. We might have gone to the 30,000-kw. turbine, as that is now an ordinary type and design; however, we only went to the 20,000-kw. turbine, as there are a number of those in actual operation today. There was no way, which we could see, to compare the operation of the 20,000-kw. unit, as a unit, other than to take a number of multiples of the smaller ones to compare with it. So far as we know, the largest gas engines in actual operation, outside of the steel industry, are those of 2000 kw. rating, and therefore we chose that size, and the same reasoning applies to the oil engine. If we multiply that by two in one case and by fifty in another case, it does not alter the relative value, and simply quoting the three machines, so as to make them comparable, is not fair to the steam turbine, unless we show what can be done with the larger sizes. That is the reason we did it.

The paper is also criticised as not covering the entire cost of the power plant. This paper is one on prime movers, and not on power plant. It seemed to us that we had to take into consideration the fuel consumption, but that we could cut out all auxiliaries. The consumption of power by the auxiliaries of the various types of prime movers is not greatly different in relative cases. The total percentage of power is from 6 to 8 per cent in nearly all cases, so that we had to make certain assumptions in order to make these comparisons on what seemed fairly equal terms.

S. Barfoed (by letter): This paper is a résumé for conditions in that section of the country where coal is obtainable at reasonable prices. In large sections of the West, however, oil is the common fuel, and the curves given under "Finance and Economics" must be revised for this condition. Assume the oil to have 18,000 B.t.u. per pound, then with

oil-fired boilers at full load a kilowatt-hour can be had from 1.26 lb. of oil, corresponding to about 259 kw-hr. per barrel of oil. With oil at 4 cents per gallon the fuel cost at full load and with oil-fired boilers will be 6.5 mills.

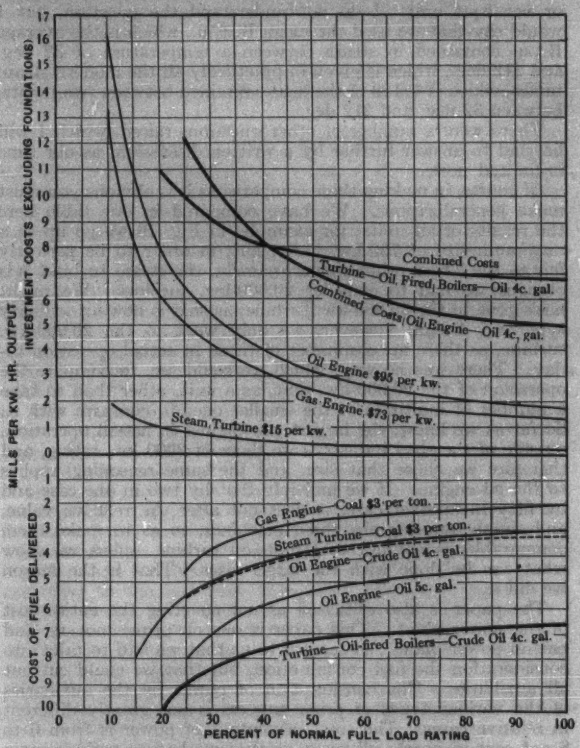

FIG. 2—RELATIVE INVESTMENT AND FUEL COSTS

Of 750-kw. steam turbine (one curve for coal firing, one for oil firing), gas engine, and oil engine, including direct-connected 60-cycle generator, operating at different percentages of normal full load.

In Fig. 2 there have been reproduced the curves of Fig. 16 in the paper and a curve has been added for a turbine with oil-fired boilers. Combining this curve with the curve for investment costs, and also the curve for the oil engine with oil at 4

cents a gallon, with the corresponding investment cost curve, it is seen that the oil engine has a considerable margin over the turbine from full load to half load. With increasing oil prices the margin would be still greater.

Franklin M. Farwell (by letter): It seems to me that the authors, without so stating, are thinking largely in terms of great capacity power stations. Almost all well-informed engineers will concede that for power stations large enough to admit of the use of units of 20,000-kw. capacity the steam turbine has no competitor, with the possible exception of water power, but when it comes to the matter of small stations it is a different story, and I believe that many engineers will question the authors' conclusions when applied to power stations of a size where all forms of prime movers are on a comparable basis.

The paper dismisses with a few brief words the reciprocating engine as if it were something not worth considering. No mention was made of a form of generating plant popularly known as the "locomobile." Many prime movers of this type are in use in various parts of the world and at least two concerns are selling them in this country now. These engines are especially adapted for driving generators of 600 kw. or under and many tests have demonstrated that the thermodynamic efficiency closely approximates that of the gas engine, and there are many who will question the ability of the present steam turbine to equal, much less exceed, these efficiencies, except in view of the possibilities offered by the mercury boiler and turbine as brought out by Mr. W. L. R. Emmet (see TRANS. A. I. E. E., 1913, Vol. XXXII, Part II, p. 2133). These entire units, auxiliaries included, will cost about the same as a gas engine of the same rating, and very light efficiencies are covered by the manufacturers' guarantee.

In Fig. 16 in the paper, the authors attempt to make a comparison of the various prime movers on the basis of units of 750-kw. capacity. As the curves in Fig. 16 stand, the investment cost for the oil engine is eight times that of the steam turbine and that of the gas engine approximately six times that of the steam turbine. A little further on in the paper is a table giving the total investment cost per kilowatt of stations using various forms of prime movers. According to this table the cost of an oil engine station is less than twice the cost of a steam turbine station, while the cost of a gas engine station is only slightly over twice the cost of a steam turbine station. There is a very evident discrepancy here. This discrepancy is doubtless due to the fact that in Fig. 16 the investment cost in the case of the oil engine covers practically a complete generating unit, but in the other cases only part of the complete generating unit is considered, as the producer in the case of the gas engine and the boiler in the case of the turbine are left out of consideration. It seems to me that this is a decidedly unfair comparison; that the producer in the case of the gas engine and

the boiler in the case of the steam turbine are the primary generators of power and cannot consistently be left out in comparison with oil engines.

As the high economy of fuel in a steam turbine is largely dependent upon a good vacuum and high superheat, in other words, is to a considerable degree dependent upon expensive

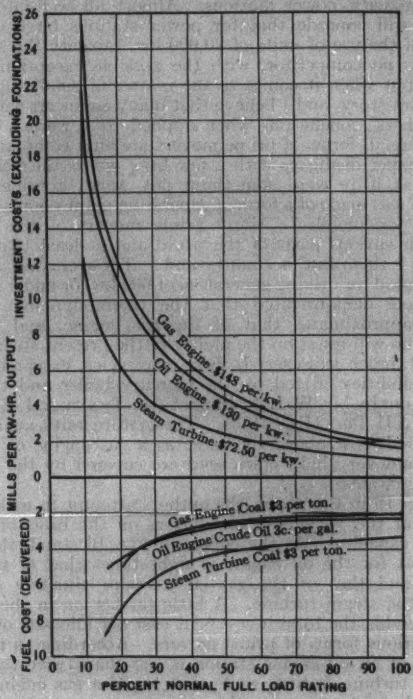

FIG. 3

auxiliary equipment, it would seem no more than fair to include the auxiliaries. Much has been claimed for the small space required for the steam turbine, but in most such comparisons no account is taken of the boiler plant. If the boiler plant is considered when comparing the space economy of the steam turbine with oil engines for small power stations, the steam

turbine does not appear to have much advantage. In view of this it seems to me that total station cost is the only fair basis for investment cost comparison.

The table of total investment cost per kilowatt included in the paper gives values for a large capacity station, but if we add to them the engine cost differences between Figs. 16 and 17, viz., $10 for oil engines, $8 for gas engines and $7.50 for the steam turbine, we have $148 for the gas engine, $130 for the oil engine and $72.50 for the steam turbine, which would seem to be reasonable for a station using 750-kw. units. On the basis of these figures I submit, in Fig. 3 herewith, a revision of the curves in Fig. 16. Concerning the lower part of the figures, showing the fuel costs, I desire to state that it seemed to me that the values given for the steam turbines are rather lower than are commonly found for working conditions, so in the accompanying curves I have boosted up the values to what seem to me to be more reasonably attainable figures with turbines of such small size. Concerning the oil engine, I find that there are several authentic cases where the total operating cost, exclusive of attendance, is considerably below that given in Fig. 16 for fuel alone, and that there are regions where crude oil can be purchased for as low as 2.5 cents per gal. In the curve submitted I have used 3 cents per gal. I believe that some of the manufacturers of oil engines are willing to guarantee a higher thermal efficiency than that given in the paper, but I neglected that in the curves. The fuel costs for the gas engine I did not find any reason for changing. It seems to me that the curves in Fig. 3, at least insofar as they concern the investment cost, are a much fairer basis for the comparison of prime movers for small plants than the curves submitted by the authors of the paper.

By adding the ordinates for investment cost and fuel cost in the curves I have given, it is apparent that there is very little difference among the three forms of prime movers. If we consider even smaller stations, say those with units of about half the size of those considered in the curve, the oil engine and the gas engine will have a decided advantage over the steam turbine. It is worth while to note in the case of the gas engine and oil engine that jacket water and water heated by exhaust heat economizers can be used for heating and for industrial processes where hot water is needed, thus extracting still more heat from the fuel without in any way affecting the engine efficiency.

I do not think that any one type of prime mover can be made to meet all cases. I believe in selecting the one best adapted to the local requirements.

While there are many central stations of enormous capacity, still a very large percentage of power generated, particularly in industrial plants, is produced in stations using units of 750 kw. or less, so it seems to me that the paper under discussion,

considering the scope it is intended to have, hardly gives the status of prime movers for small stations with the fairness that ought to be expected.

W. S. Gorsuch (by letter): Curves shown in Figs. 16 and 17 have been criticised as being unfair to the oil and producer or natural gas engines. In Fig. 16 the largest oil engine for which reliable data could be obtained was taken as the basis, and a corresponding size gas engine and steam turbine selected for comparative purposes. In fact, the largest oil engine unit in successful operation in this country today is less than 500 h.p. capacity; therefore, in taking a unit of 750 h.p., the oil engine is being favored.

The object of Fig. 17 is to show the advantage that the steam turbine has in being made in large sizes, 20,000 kw. being taken, as many such units are in actual operation. To make the curves showing investment costs comparable, the cost per kilowatt normal rating was determined on the basis of purchasing 10 producer gas and 40 oil units of the largest sizes in actual operation today. The lower curves show the relative economy of the individual units and have no reference to plant operation.

Regarding Mr. Tschentscher's comments on "Space Economy," the figures given on the last page of the paper are the average minima and maxima of different sizes of machines in actual operation today, excluding the blast furnace gas engine.

If Mr. Farwell will refer to page 978, under the heading "Finance and Economics" he will find it specifically stated that the scope of this paper is limited to prime movers; consequently the upper curves in Figs. 16 and 17 show the investment costs in units per kilowatt-hour output at various percentages of full-load rating for prime movers only, that is, the cost of prime mover installed, exclusive of foundation. The figures given in the table on page 1163 give investment costs of plants using various types of prime movers, and include all costs, with the exception of real estate.

The figures and curves submitted by Mr. Farwell are based on the assumption that the investment cost per kilowatt installed capacity of all the items contained in a small power plant, exclusive of the prime mover, will be the same as for a station of much larger capacity, which obviously is erroneous. The cost of fuel per kilowatt-hour output for the steam turbine, as given in Fig. 16, is based on the average efficiency obtained from this size machine.

R. J. S. Pigott (by letter): Replying to Mr. Tschentscher, if he will refer to page 1143, under the heading "Capacity," no doubt the question in his mind will be removed as to the relative overload capacities on gas engines and turbines. While his figures in criticism of our costs are somewhat indefinite as a basis of analysis, the figures presented in our paper were obtained from a number of manufacturers and from purchase prices in the hands of a number of buyers.

Referring to the statement of Mr. Farwell concerning the locomobile: This type of prime mover has been installed in this country in less than half a dozen small plants, the first early in 1913. Few or no maintenance data are available, but it is certain that with the high superheats employed, the maintenance will not be less than with the ordinary reciprocating engine using superheat. The inflexibility of a type in which one boiler is definitely tied to one engine is a very pronounced objection. The very high "efficiencies" usually quoted, are water rates, which naturally, with the high superheat and re-heat employed, are low, but low water rate is not necessarily concomitant with high efficiency.

Referring to the Rankine cycle, the performance of locomobiles is little better than that of ordinary reciprocating engines. Table I, herewith, taken from tests of the first American locomobile, published in *Power* May 20, 1913, shows this. With similar superheat and re-heat the turbine would do equally well, and if worth while to do it, could readily be arranged in a similar manner to the locomobile.

TABLE I

Test	Brake h.p.	Lb. Steam b. h. p.-hr.	Pressure lb. gage.	Vacuum, in. of Hg.	Superheat	Therm. effic'y	Efficiency ratio
3	127	10.82	196.5	27.15	256.	18.7	62.5
4	148	11.08	206.5	26.62	273.	18.3	60.7
5	115	10.9.	201.5	28.58	227.6	18.2	55.9
6	154	11.45	198.5	27.27	273.5	17.5	57.7
7	192	10.25	204.	27.23	302.	19.4	62.8
10	77	14.65	200.	27.75	170.4	14.2	46 5

Presented at the 31st Annual Convention of the American Institute of Electrical Engineers, Detroit, Mich., June 25, 1914.

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VOLTAGE TESTING OF CABLES

BY W. I. MIDDLETON AND CHESTER L. DAWES

Abstract of Paper

In this country rubber compound, paper, and cambric are generally used for cable insulation. From the formula $S = \frac{0.868\,V}{d \log_{10} \frac{D}{d}}$, the stress at any point in a homogeneous insulation may be determined. The minimum stress and the maximum allowable voltage occur when the conductor is 10/27 of the sheath diameter. The present irrational practise of testing cables should be standardized to conform to this formula or a modification of it.

Over-stressing of the insulation is accompanied by a change of insulation resistance and electrostatic capacity.

No one factor of safety is applicable to every cable system, but one must consider the conditions of operation as well.

In testing the voltage may be applied: (1) by submersion; (2) between the conductor and metallic sheath; (3) between wires. The submersion test is the most severe. A sine wave is desirable for testing purposes, but rarely occurs in a commercial generator under these severe conditions of load. Reactance cannot always be used successfully to reduce the volt-ampere load on the generator.

With a distorted wave an a-c. voltmeter gives only a poor indication of the maximum voltage. The writers have devised an instrument based on the oscillograph principle, with which the maximum voltage may be determined, regardless of wave form.

THE design of cables is largely dependent on data obtained from voltage tests made on commercial lengths. Such tests are usually conducted in the testing-room but are frequently made after the cable has been installed. The importance of this subject has led the writers to present such data as may seem either useful or of interest in connection with the design or testing of cables, and further, to enumerate some of the difficulties encountered in making such voltage tests, together with the methods adopted to eliminate these difficulties.

Insulating Materials

In this country, three materials are in general use for the insulation of wires and cables; rubber compound, varnished cambric, and paper.

Rubber compound is the oldest, and is the only one that can be used under all conditions without the aid of a lead sheath. Its composition is more complex than that of the others, involving pure rubber, certain mineral ingredients, and hydrocarbons. The number of such ingredients and the proportion of each that can be used has allowed a great number of compounds to be made and has led to considerable discussion as to the value of some of these as insulating materials.

Paper as an insulation for wires and cables is used in two ways: wrapped on loosely and kept dry, as in telephone cables, or put on tightly and saturated with some good insulating oils or compound. The insulating properties of this class of cable depend absolutely on the soundness of the lead sheath.

Varnished cambric is the most recent material used for cable insulation and stands between rubber and paper; it has a number of good qualities. Being a cotton fabric coated on both sides with several films of insulating varnish, it is almost waterproof, and may be submerged in water for a considerable length of time without undue deterioration. In the process of manufacture, the varnished cloth is applied spirally in the form of tape, a viscous insulating compound being simultaneously applied between layers.

Voltage and Stress Formulas

Theoretically, the stress at any point on a homogeneous cylindrical insulation may be determined from the following formula:

$$S = \frac{0.434\ V}{X \log_{10} \frac{R}{r}} \tag{1}$$

where V = volts impressed between conductor and sheath,
r = radius of the conductor,
R = radius of the insulation,
X = distance from the axis to the point in question,
S = stress in volts per unit thickness of insulation at this point.

The stress will be a maximum at the surface of the conductor. Therefore letting $X = r$, $r = d/2$, and $R = D/2$, the stress at the surface of the conductor becomes

$$S = \frac{0.434\ V}{\frac{d}{2} \log_{10} \frac{D}{d}} = \frac{0.868\ V}{d \log_{10} \frac{D}{d}} \tag{2}$$

where d = diameter of the conductor,
D = diameter of the insulation.

This relation is shown in Fig. 1.

With D and V fixed, the maximum stress at the surface of any insulated wire will be inversely proportional to $d \log_{10} \frac{D}{d}$. It will therefore diminish with an increase in the diameter of the conductor, until a minimum is reached, after which the stress will increase with further increase of conductor diameter. This minimum may be found by differentiating formula (2), and

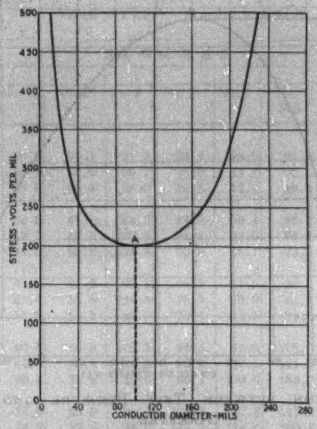

FIG. 1—CURVE OF STRESS AND CONDUCTOR DIAMETER.
Voltage (V) constant at 10,000. Diameter over insulation (D) constant at 272 mils.

equating to zero, and the value of d corresponding thereto is found to be $D/\epsilon = D/2.72$ where ϵ is the Napierian base. This relation plotted with volts per mil as ordinates and conductor diameter as abscissas, is shown in Fig. 1. Point A shows the point of minimum stress. The wire diameter for minimum stress is about 10/27 of the diameter of the insulation.

If in formula (2), D and the maximum allowable stress S are kept constant, and the voltage is allowed to vary with the conductor diameter, we have

$$V = \frac{Sd}{0.868} \log_{10} \frac{D}{d} \tag{3}$$

This relation is shown in Fig. 2. Under these conditions the maximum voltage that we may impress between the conductor and the outside, without exceeding the allowable stress, occurs when $d = D/2.72$.

This does not mean, however, that if this maximum voltage were impressed upon the cable when d is less than $D/2.72$ the insulation would break down, but rather that the wall of insulation between the diameter $D/2.72$ and the conductor would be

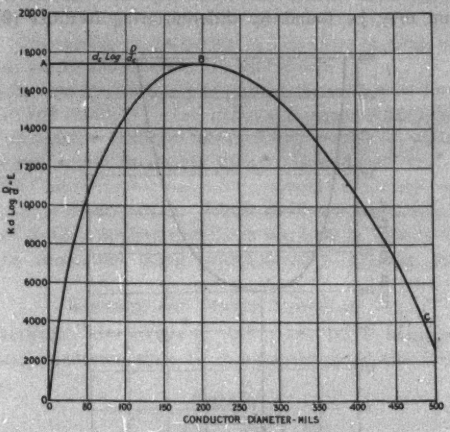

FIG. 2—RELATION BETWEEN TEST PRESSURE AND CONDUCTOR DIAMETER.

$E = K\,d \log D/d$. $K = 200$. $D = 544$ mils. Stress constant.

All wires having the same outside diameter whose conductor diameter is equal to or less than $D/2.72$ ($= d_c$) should have the same breakdown voltage.

stressed beyond the allowable limit. The layer nearest the conductor is under the maximum stress, and the stress in any other layer is inversely proportional to its distance from the center if the electrical characteristics of the insulation remain unchanged. Theoretically, then, all cables having d less than $D/2.72$ should break down at the same voltage, hence follow the line ABC, if it be assumed that the voltage drop across the over-stressed layer is practically zero.

Although there has been no evidence, so far as the writers

know, that these inside layers are actually broken down under these conditions, it is a well-known fact that the dielectric constant of an over-stressed dielectric is greater than the normal constant before breakdown, and this tends to reduce the voltage drop across the inner layers and throw more stress on the outer wall. Whether or not this be true, experience indicates that the breakdown occurs along the line AB, Fig. 2, and little or nothing is gained in making d less than $D/2.72$.

The following formula has therefore been adopted as most

TABLE I

Values of $d \log \frac{D}{d}$. D and d in mils

Wall (in)	Size Wire B. & S.								
	No. 14	No. 12	No. 10	No. 8	No. 6	No. 4	No. 1 Std.	4/0 Std	1,000,000 Cir. Mils
1/32	19.1	20.0	21.3	21.9	22.8	23.9	24.8	25.6	26.2
3/64	25.2	27.1	28.9	30.7	33.0	33.7	36.0	37.6	38.8
2/32	30.3	33.0	36.4	38.0	40.5	42.4	46.0	49.4	51.6
5/64	34.5	38.0	41.1	44.2	47.6	50.4	55.5	59.5	64.0
3/32	38.4	42.2	46.3	50.4	54.4	58.0	64.5	70.0	75.5
7/64	41.6	46.0	50.8	55.6	60.0	65.1	73.0	79.6	87.1
4/32	44.6	49.5	54.9	60.4	65.9	71.0	80.7	89.0	98.4
9/64	47.2	52.7	58.6	64.8	70.9	76.9	88.1	97.6	108.9
5/32	49.7	55.5	62.2	69.0	75.6	82.5	95.5	107.0	119.2
6/32	54.0	60.8	68.3	76.3	84.5	92.5	108.5	123.2	141.1
7/32	57.7	65.3	73.8	82.9	92.2	102.0	121.0	138.9	161.2
8/32	61.0	69.3	78.6	88.8	99.1	110.0	132.0	153.0	180.4
9/32	64.0	72.9	83.0	94.1	105.3	117.3	141.0	166.2	198.8
10/32	66.3	76.2	87.0	98.9	111.3	124.5	150.5	179.3	217.0

nearly representing the breakdown stress for small conductors with a heavy wall of insulation.*

$$S = \frac{0.868\ V}{d_c \log_{10} \frac{D}{d_c}} \tag{4}$$

where $d_c = D/2.72$.

Potential Stresses in Dielectrics, by H. S. Osborne, TRANS. A. I. E. E., 1910, Vol. XXIX, part 2, p. 1553.

Discussions, by W. I. Middleton, p. 1587; Henry A. Morss, p.1589; Wm. A. Del Mar, p. 1614.

The maximum voltage that may be safely impressed upon a cable of a given insulating material is proportional to $d \log_{10} \frac{D}{d}$, and to a constant K, depending on the quality of material (formula 3).

Values of $d \log_{10} \frac{D}{d}$ are given in Table I, for walls from 1/32 in. (0.794 mm.) to 10/32 in. (7.94 mm.) thick on various wires from No. 14 B. & S. to 1,000,000-cir. mil cable, and these values are plotted in Fig. 3. These tables and curves are very

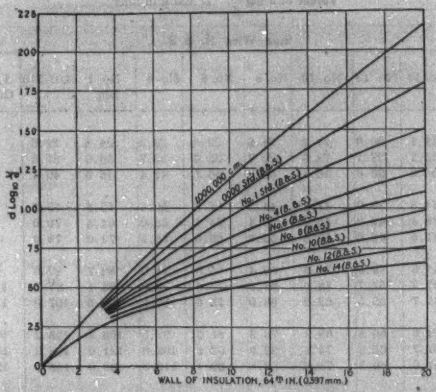

FIG. 3—RELATION BETWEEN d LOG$_{10}$ D/d AND WALL OF INSULATION. "d" AND "D" IN MILS

useful in the application of the formula to cable testing, for the value of K only needs to be known to determine the allowable voltage test or proper diameter. When d is expressed in mils, K varies from 100 to 250 for rubber compounds, is about 250 for cambric, and for paper with thin walls is much less than 250 but is greater than this for walls exceeding 10/32 in. (7.95 mm.).

STANDARDIZATION OF VOLTAGE TESTS

Until recently no attempt has been made to standardize voltage tests on insulated wire and cables with reference to the theoretical stress. The result is a chaotic condition of affairs. A very

common rule has been to specify a test of 2½ times the working pressure, the feeling being that this allows a good factor of safety. This rule might be satisfactory if the wires were all of one size and the same wall of insulation used for each working pressure. As such is not the case, the only rational way to test all cables is by the $d \log_{10} \frac{D}{d}$ rule or a modification of it.

On October 1, 1905, the Underwriters' Laboratories specified that all Code wires for voltages between 0 and 600 volts should be tested after ten hours immersion in water, with 1500 volts (alternating current) for not less than five seconds. That specification showed the influence exerted on most engineers at that time by the factor of 2½ times the working pressure.

A little study of Fig. 3 together with the sizes of wires and walls of insulation made under the code specifications shows how absurd this test was. The conductors varied from No. 14 to 1,000,000 cir. mils and larger (0.064 to 1.156 in. or 1.63 mm. to 29.4 mm. in diameter); the wall of insulation from 3/64 in. (1.19 mm.) to 7/64 in. (2.78 mm.), (0.469 to 0.109 in.). If the 3/64 in. (1.19 mm.) wall of insulation on the No. 14 would stand 1500 volts, it should surely stand much more than this on the 1,000,000 cir. mil. It would therefore be possible for the 1,000,000-cir. mil cable to meet this test even were the wall of insulation defective or actually less than 3/64 in. (1.19 mm.) in places, whereas the main object of the voltage test is to break down any such faults.

The 1911 Code specifications for 0 to 600 volts have, in part, remedied this defect by calling for a test of the 1,000,000 cir. mil at 3500 volts, but at the higher voltages they still hold to 2½ times the working pressure. The specifications of some of the largest buyers in the country today are equally inconsistent.

This is a lamentable condition. It allows too much variation in the dielectric strength of the insulating materials. Some of this variation may be due to ignorance, and some may be intentional. When a cable is tested at only one-half the voltage to which it should be subjected, there results in many instances a carelessness in its manufacture. The writers believe that too little has thus far been accomplished in the line of the standardization of cable testing, when compared with other branches of engineering.

The following tests, in Tables II and III, are recommended for high- and medium-voltage cables, respectively. Table IV, on

TABLE II

RECOMMENDED VOLTAGE TESTS FOR HIGH-VOLTAGE CABLES.

30 per cent Para Rubber

Wall of insulation (in.)	3/64	2/32	5/64	3/32	7/64	4/32	5/32	6/32	7/32	8/32
550,000 cir. mil and larger					14,000	16,000	19,000	22,000	25,000	28,000
500,000 cir. mil to 250,000 cir. mil.					13,500	15,000	18,000	20,500	23,000	26,000
4/0 to 1 B. & S.			11,000	12,000	13,000	14,000	17,000	19,000	21,000	24,000
2 to 4 B. & S.			10,000	11,500	12,500	13,500	16,000	18,000	20,000	22,000
6 B. & S.		8,000	9,500	11,000	12,000	13,000	15,000	17,000	19,000	21,000
8 "	6,000	7,500	9,000	10,000	11,000	12,000	14,000	15,500		
10 "	6,000	7,500	8,000	9,500	10,000	11,000	12,500	13,500		
12 "	5,500	6,500	7,500	8,500	9,000	10,000	11,000	12,000		
14 "	5,000	6,000	7,000	7,500	8,000	9,000	10,000	11,000		

the other hand, is the specification as called for by a purchaser for the cables listed in Table III. It will be seen that the testing pressure recommended is from 1½ to 2½ times that called for by the purchaser. As far as working pressure is concerned, the factor of safety demanded by the purchaser in Table IV is, without doubt, sufficient. Yet the tests called for by this table would not begin to show up any but the most serious defects in the insulation of the respective cables.

The *A. R. E. E. committee on "Wire and Cable Specifications" has taken the most important step thus far in the standardization of voltage tests for cables, in its recent recommendations for tests on rubber, cambric and paper insulation.

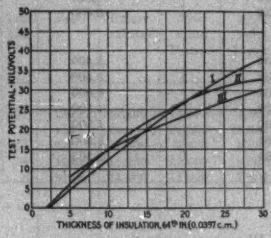

FIG. 4—POTENTIAL TESTS ON CONDUCTORS, RECOMMENDED BY A. R. E. E. No. 1 TO No. 4/0 A. W. G.

I. Paper or varnished cambric.
II. Rubber.
III. 155 $d \log_{10} D/d$ for No. 1 A.W.G.

From Fig. 3 it will be noted that there is but a relatively small difference in the values of $d \log_{10} \frac{D}{d}$ for diameters corresponding to No. 1 and No. 4/0 B. & S. gage, consequently one set of values covering these ranges has been recommended, and is plotted in Fig. 4.

Curve I is recommended for paper and varnished cambric, curve II for rubber, and curve III is the value of $K\, d \log_{10} \frac{D}{d}$ when $K = 155$ and d and D are given in mils. Up to a 20/64-in. (7.95-mm.) wall the paper and cambric are rated at a lower working pressure than the rubber, for mechanical reasons, but above this they should test even better than the rubber.

OVER-STRESSING CABLES

Much has been said in the past relative to unduly severe testing conditions in that the insulation, initially sound mechanically, becomes stressed beyond the electric elastic limit when tested. Although the short duration of the test may not develop any faults, the cable is nevertheless permanently injured, hence less able to withstand the shocks incidental to service conditions. This may be the case, but fortunately the insulation resistance

*Association of Railway Electrical Engineers.

TABLE III

Recommended Voltage Tests for Low-Voltage Cables.

INSULATED WITH LOW-TENSION RUBBER COMPOUND. VOLTAGE TEST AT FACTORY, FIVE MINUTES AS PER TABLE; VOLTAGE TEST AFTER INSTALLATION, 30 MINUTES AT 50 PER CENT OF TABLE VALUE.

Size conductor	Minimum thickness insulation, inches.	Test pressure, volts.
Stranded		
1,000,000 cir. mils	4/32	10,000
750,000 "	4/32	10,000
500,000 "	4/32	9,000
350,000 "	4/32	9,000
4/0 A. W. G.	3/32	7,000
2/0 "	3/32	6,500
1/0 "	3/32	6,500
2 "	3/32	6,000
Solid		
4 A. W. G.	3/32	5,500
6 "	3/32	5,500
8 "	3/32	5,000
10 "	3/32	4,500
12 "	3/32	4,000
14 "	5/64	3,500
14 (3) " conductor	5/64	3,500

TABLE IV

Voltage Tests as Specified by a Purchaser.

TESTS ON CABLES INSULATED WITH LOW-TENSION RUBBER COMPOUND. VOLTAGE TEST AT FACTORY, FIVE MINUTES AS PER TABLE; VOLTAGE TEST AFTER INSTALLATION, 30 MINUTES AT 50 PER CENT OF TABLE VALUE

Size	Strands.	Wall.	Volts working pressure	Volts test pressure
Stranded				
1,000,000 cir. mils.	61	4/32	1000	4000
750,000 "	61	4/32	"	4000
500,000 "	37	4/32	"	4000
350,000 "	37	4/32	"	3000
4/0 A. W. G.	19	3/32	"	3000
2/0 "	19	3/32	"	3000
1/0 "	19	3/32	"	3000
2 "	7	3/32	"	3000
Solid				
4 A. W G.		3/32	1000	3000
6 "		3/32	"	3000
8 "		3/32	"	3000
10 "		3/32	"	3000
12 "		3/32	"	3000
14 "		5/64	"	2000
14 "	3-Cond.	5/64 (no belt)	"	2000

and the electrostatic capacity enable us to determine the degree to which the insulation has been over-stressed.

Immediately after the stress is applied, the insulation resistance, measured with direct current, may drop considerably below its initial value as obtained a few moments previous to the application of voltage. This change may be as great as 50 per cent. If further readings of insulation resistance are taken, they will show a gradual increase and will approach their initial value

TABLE V

WIRES SHOWING RESULTS OF STRESS.

Megohms in 1000 ft.

Test No.	Feet	Before voltage	2500 volts 1 min.	5000 volts 1 min.	After 2 hours	5000 volts 5 min.	After 2 hours	
1	1562	14,500	14,500	7,500	11,500			
2	1547	22,000	22,000	16,000	18,000			
3	3150	7,500	7,500	6,000	7,000	5,000	5,000	
4	1740	15,000	15,000	6,500	10,000	750	2,500	
5	2402	15,000	15,000	7,500	10,000	2,500	3,500	
							Break-down voltage	Megohms in 1000 ft. after repair. 4000 volts, one min.
6	3560	4,800				4,620	13,000	4,400
7	1425	3,500				3,440	12,000	4,470
8	2350	9,000				9,015	15,000	8,425
9	2750	7,660				7,660	15,000	9,150
10	2400	2,950				2,740	7,500	2,810

if the cable has not been over-stressed, whereas, if it has been over-stressed, the resistance recovers but little. Care must be taken to keep the temperature constant during these tests, for insulation has a very large resistance temperature coefficient. Table V shows some typical data taken from tests made on long lengths of wire as they were passing through the testing room.

The insulation resistances in tests (1) and (2) were affected considerably after the 5000-volt one-minute test, but practically recovered after two hours. It is possible that they would have

completely regained their initial resistance if allowed sufficient time.

Tests (3), (4) and (5) were first made under the same conditions and, except in the case of (3), the recovery was much poorer than in the former cases. They were then subjected to 5000 volts for five minutes, with a noticeable reduction in the resistance of (3) and a very large and permanent reduction in that of (4) and (5). These last two were permanently injured.

In tests (6) to (10) inclusive, there was no marked decrease in resistance after the 5000-volt test, so they were broken down, repaired by patching the faults, tested at 4000 volts for one minute, and the insulation resistance measured again, with the results shown in the table. Tests (7) and (9) gave even better

TABLE VI

WIRES SHOWING THE RESULTS OF STRESS.

Microfarads per 1000 ft.

Feet	Before voltage test	After 5000 volts for 1 min.
3150	0 126	0.130
2176	0.146	0.150
2470	0.130	0.134
2925	0.130	0.133
2775	0.120	0.124

results than the initial resistances, due no doubt to patching a localized fault.

Unfortunately, the electrostatic capacity of these cables was not measured after every application of voltage, but Table VI shows in a general way the increase of capacity due to stress in the dielectric. For a given stress the change in capacity is much smaller than the change in resistance.

These results show that it is possible to make a rubber compound which is not easily stressed beyond the electric elastic limit, and further, that if a compound is so stressed it is possible by means of the insulation resistance to determine if the test has been too severe.

FACTOR OF SAFETY

It is not the intention of the writers to tell the operating engineers what should be the factor of safety in a cable system. Great fear has been expressed now and then, that engineers, knowing

that cables will stand these high-voltage tests, will be tempted to use them on higher working pressures than they should. In this connection it is well to bear in mind that a factor of 2½ times the working pressure is not applicable to all conditions.

(1) *In two systems of the same kilowatt capacity the cables on that system having the lower voltage should have the greater factor of safety.* This is because the surge voltage on the lower-voltage system will be greater because of the greater current, and the maximum possible rise in voltage is $e = i\sqrt{\frac{L}{C}}$, where i is the amperes current transient, and L and C the system inductance and capacity, expressed in henrys and farads respectively.

(2) *In two systems having the same voltage, those cables operating on the system having the greater kilowatt capacity should have the greater factor of safety.* The reason for this is obvious. As has been frequently observed, transients that are practically unimportant in a small system become dangerous if allowed to take place in a large system. The writers have in mind a case where 2300-volt distributing cables, when connected to a relatively small plant, gave practically no trouble, but later, when this smaller system received its energy from a large transmission network, these same cables, though *normally* operating at the same voltage as before, gave so much trouble that they had to be replaced by cables better suited to the conditions.

Method of Testing

The voltage test can be applied to wires and cables in several different ways; by submerging the cables in water; testing them against a metallic covering on the outside such as a lead sheath or tin foil; and testing one wire against another when there is more than one wire in the cable. The submersion test is the most severe, as the water makes very close contact with the outside of the cable, regardless of any surface irregularities that may be present. The water also has a tendency to penetrate into any foreign substance that may be in the insulating material, provided this substance has any affinity for water.

All of these tests may be, and generally are, made on rubber insulated cables. The cambric cables to be braided are generally submerged before and after braiding; cambric cables to be lead-covered are not submerged, as considerable trouble in drying them is experienced, and as they are to be tested after the lead

covering has been applied, the submersion test is not necessary. Paper cables are not submerged, and all tests are made after leading.

The voltage test, as applied to cables, is practically the same whether it is made submerged, against the lead, or against the contiguous wires, the object being to break down any weakness that may exist in the insulation. How much pressure, and for how long it shall be applied, are questions that have long been the subject of much discussion.

For several reasons, it is necessary to apply the voltage test to the finished cable and not to a short sample. (1) It is desirable to break down any weak places that may occur in the cable, it being quite impossible to avoid entirely such places in manufacture; (2) to satisfy inspectors and purchasers that the cable meets specifications as regards dielectric strength; (3) to obtain data and information as to the dielectric strength of the material; (4) constants obtained in laboratories from tests of short lengths are not applicable to commercial lengths and are usually misleading.

Testing Apparatus*

Recommendations have appeared at different times regarding the type of generator and transformer that it is advisable to use for testing purposes, and the consensus of opinion seems to be that a smooth-core generator with field control, and a variable-ratio transformer, are most satisfactory. As will be shown later, it is doubtful if the generator of ordinary design can maintain its wave form under the severe conditions imposed by cable testing.

Where cables of some length are to be tested, a frequency of 25 cycles is preferable to one of 60 cycles, for the necessary generator and transformer capacities are practically proportional to the frequency, and according to the best information the writers can obtain there is no appreciable difference in severity of cable tests whether made at 25 or 60 cycles.

In the following tests, made in the testing laboratory of a wire manufacturer, the generator used was a motor-driven 25-kv-a., 220-volt, four-pole, 25-cycle, single-phase alternator, having 10 slots per pole, and a conductor belt $\frac{5}{8}$ the pole pitch. The transformer capacity was 50 kv-a., 220-50,000 volts. The secondary consisted of four separate 12,500-volt coils, capable of being con-

*High-Tension Testing of Insulating Materials, A. B. Hendricks, Trans. A. I. E. E., 1911, Vol. XXX, part I, page 167.

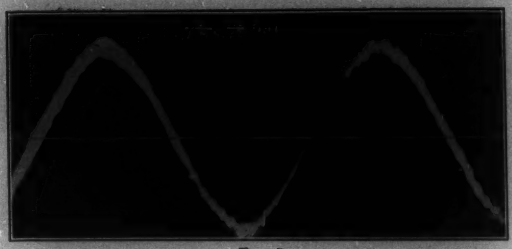

FIG. 5 [MIDDLETON AND DAWES]

FIG. 6 [MIDDLETON AND DAWES]

FIG. 7 [MIDDLETON AND DAWES]

FIG. 8 [MIDDLETON AND DAWES]

FIG. 9 [MIDDLETON AND DAWES]

FIG. 12 [MIDDLETON AND DAWES]

nected either in parallel, in series-parallel, or in series. The high-tension winding had a total of 12,512 turns, and the low-tension 55 turns. The reactance voltage was about 6 per cent.

Fig. 5 shows the generator voltage on open circuit, and except for the tooth harmonics, the e.m.f. wave is practically sinusoidal. For testing purposes, this wave is perfectly satisfactory if it could be maintained under all load conditions. In Fig. 6 is shown the generator voltage wave taken at 220 volts when the transformer is connected, and also the exciting current wave of the transformer.

This transformer exciting current is about 17 per cent of the rated load current of the transformer, but is 34 per cent of the rated load current of the generator. This is rather high, and further, Fig. 6 and other experiments showed that the transformer iron was being operated at unusually high saturation. It might well be argued that a large transformer magnetizing current is desirable, as it tends to offset the leading component of cable charging current, but it should be remembered that beyond a certain core density the additional exciting current is made up almost entirely of harmonics which do not neutralize the fundamental. Experience has shown this to be undesirable for other reasons. Examination of the current wave in Fig. 6 shows that the transformer takes a pronounced third harmonic current, and this current reacting on the generator flux tends to start wave distortion, producing a third harmonic in the e.m.f. wave as shown. If a cable, like most other electrical apparatus, took a comparatively small charging current, most of the following difficulties, due to wave distortion, would disappear.

Figs. 7, 8 and 9 show various voltage waves actually obtained under different conditions of test. The voltages on the cables, given in connection with all the following oscillograms, are according to the ratio of transformation, hence, are not strictly correct. In actual practise this voltage is determined directly from the high-tension side by means of a potential transformer.

The reasons for this distortion are obvious. The generator may have, inherently, a sine wave voltage, but the transformer exciting current has a prominent third harmonic. This current and the single-phase pulsating armature reaction produced on the flux wave, will usually introduce harmonics in the voltage wave as shown in Fig. 6. This wave is communicated to the transformer secondary where the cable intensifies it in its charging current, and it is reflected back in the generator current, and increased

wave distortion results. These reactions are cumulative and will continue to increase until counter-reactions set up in the magnetic and electric circuits become sufficiently great to balance them. Generator saturation, generator and transformer series leakage reactance and the phase relations of the harmonics may tend to counteract distortion. The value of series reactance may

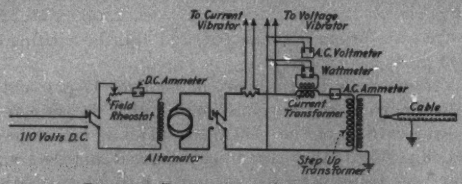

FIG. 10—DIAGRAM OF CONNECTIONS

be such as to produce resonance for one harmonic and not the others.

The generator may be represented by a coil that is a source of voltage and having reactance and resistance; the transformer may be replaced by a shunt impedance, of a value equal to the open-circuit impedance of the transformer, and by two series impedances, one representing the equivalent resistance and leak-

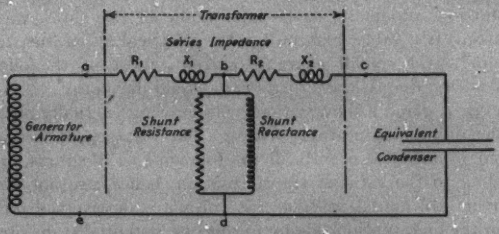

FIG. 11—EQUIVALENT CIRCUIT DIAGRAM

age reactance of the primary side, and the other the impedance of the secondary reduced to the primary side; the cable represents a condenser referred to the primary side and having a very high effective resistance. Fig. 11 shows this condition.

The shunt impedance *b d* has a decided effect on the generator wave form, in that its current wave, especially at the higher voltages, is mostly made up of harmonics, and these, reacting on the

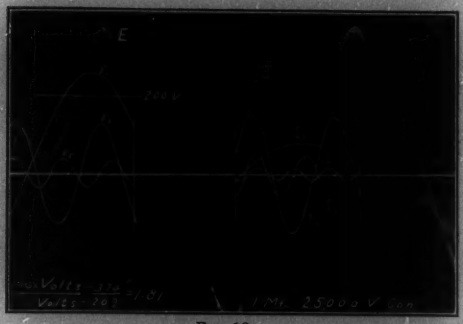

FIG. 13 [MIDDLETON AND DAWES]

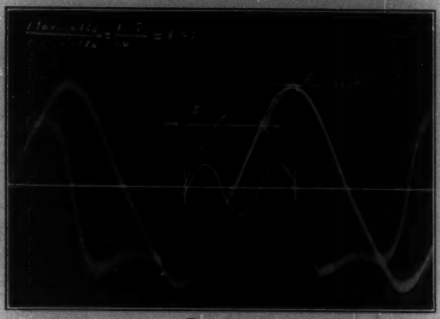

FIG. 14 [MIDDLETON AND DAWES]

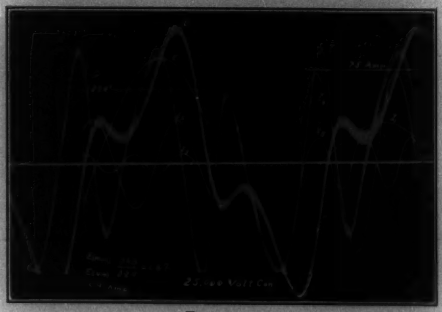

FIG. 15 [MIDDLETON AND DAWES]

FIG. 16 A [MIDDLETON AND DAWES]

FIG. 16 B [MIDDLETON AND DAWES]

FIG. 16 C [MIDDLETON AND DAWES]

FIG. 17A [MIDDLETON AND DAWES]

FIG. 17B [MIDDLETON AND DAWES]

FIG. 17C [MIDDLETON AND DAWES]

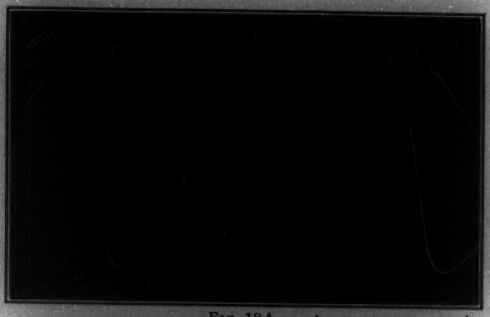

FIG 18A [MIDDLETON AND DAWES]

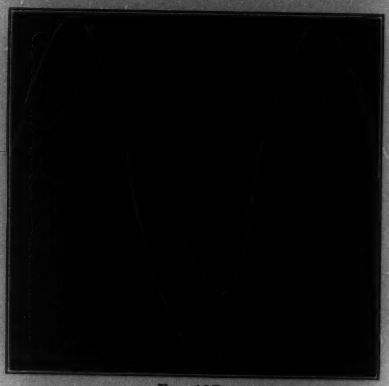

FIG. 18B [MIDDLETON AND DAWES]

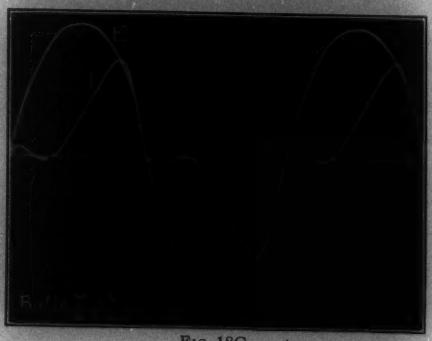

FIG. 18C. [MIDDLETON AND DAWES]

generator flux, are responsible for the initial distortion to which reference has been already made. The series circuit *a b c d e*, consisting of the transformer primary and secondary resistances and leakage reactances and the condenser, all in series with the generator armature, exerts some influence on the generator wave form. The magnitude and shape of the generator current wave may be dependent on the relation of inductance to capacity in this circuit. Therefore, harmonics may be intensified or diminished, depending on their frequency, on the transformer inductance and the cable capacity. These effects are illustrated in Figs. 12 to 15 inclusive.

The oscillograms shown in Figs. 12 and 13 were taken when a cable having a capacity of 0.1 microfarad was connected to the transformer secondary, and those shown in Figs. 14 and 15 were taken with another cable having a capacity of 0.13 microfarad, connected to the transformer secondary. Two tests were made with each cable; one in which all four of the transformer secondary coils were connected in series (50,000-volt) connection, the other in which the series-parallel (25,000-volt) connection was used. In order to compensate for the change in transformer ratio so that the effective voltage on the cable should remain approximately unchanged, the generator voltage was practically doubled when the change was made from the 50,000-volt to the 25,000-volt connection.

Figs. 12 and 14 show the results obtained with the 50,000-volt connection, and in each case the e.m.f. wave is very nearly sinusoidal, and no appreciable harmonics above the third, appear in the current wave. In each of these cases the generator was operated at low saturation, a condition in which it would be less able successfully to oppose severe reactions on the flux wave. The natural frequency of the transformer and cable circuit in the case of Fig. 12 is 110 cycles, and of Fig. 14, 96.6 cycles. The shunt circuit *b.d*, owing to the variable nature of its inductance, would be difficult to take into consideration, except in a very general way, and was consequently neglected in this frequency determination.

In Figs. 13 and 15, the approximate sinusoidal e.m.f. waves shown in Figs. 12 and 14 are distorted, containing fair-size fifth harmonics, and third harmonics about 50 per cent of the fundamental. In each case the current wave is even more distorted than the e.m.f. wave, showing a seventh harmonic, a fifth equal in magnitude to the fundamental and a thirdabout twice as

great as the fundamental. In these cases, the natural frequency of the circuit was 215 and 192 cycles respectively.

Thus in each case, with the same generator, the same transformer, the same frequency and the same cable, an approximate sine wave is converted into a complex wave by simply changing the transformer ratio and the generator voltage. These phenomena cannot be explained on the basis of a resonant series circuit, for the best wave shapes were obtained when the circuit constants were more conducive to the flow of the troublesome third and fifth harmonics. However, in these two latter cases the transformer exciting current contains harmonics of very appreciable magnitude as shown in Fig. 6, and in the writers' opinion, these harmonics are practically responsible for the results that were obtained.

It might also be added, referring to Fig. 11, that in the circuit *a b c d*, the resistance is very small, thus offering excellent opportunities for oscillations to take place during the transient or building-up condition. Great care must be exercised in raising and lowering the voltage, as the possibility of building up an abnormal potential across the cable is always present, and this may result in a puncture.

Specific illustrations of this have come to the writers' attention on several occasions. When the voltage across a cable was being gradually raised, the spark-gap, connected in parallel, would discharge light sparks, momentarily, when the switchboard voltmeter indicated that the potential across the gap was only half that at which the gap was set. If the voltage was held constant for an instant, the sparking would discontinue, and the voltage could then be raised cautiously without further disturbance. The fact that the gap was not ruptured showed that a transient rise of voltage occurred, but that there was insufficient energy to cause a dynamic arc.

Use of Reactance

It occurred to the writers that the generator current might be considerably reduced by using a shunt reactance to neutralize the leading component of the cable-charging current, thus securing a better wave form by reducing the ampere load on the generator. This has been tried abroad* and also by the Edison Electric Illuminating Co. of Boston.†

Elektrotechnischer Zeitschrift, Feb. 27, 1908.

†"High-Potential Cable Testing at Boston," by C. L. Kasson, *Electrical World*, Vol. 60, p. 354.

We made nine tests, and in every case the same cable was used, namely 1000 ft. (305 m.) No. 1/0, 7/32 in. (5 56 mm.) wall, rubber insulation, having a capacity of 0.175 microfarad. Three different tests were made at each of three different voltages. At each voltage: first, the oscillogram was taken without the reactance; second, the reactance was adjusted until the line current was a minimum; and third, the reactance was adjusted for the best voltage wave form. The results of these tests are shown in Figs. 16A to 18C inclusive.

The following conclusions are to be drawn from the above tests:

(1) The point of minimum current does not necessarily correspond to the best wave shape.

(2) The best wave shape may occur at an abnormally large value of lagging current.

(3) The wave can not be made sinusoidal in every case.

(4) At the point of minimum current (usually denoting resonance for a parallel circuit) the power factor is below 50 per cent in two cases, and 70 per cent in the third, and the waves are not necessarily in phase.

Further, in Figs. 18A, 18B and 18C, when the generator voltage was low, there was but slight distortion in the e.m.f. wave, which tends to confirm the previous theories as to the effect of the transformer exciting current on the e.m.f. wave.

Thus with a commercial generator and transformer, the e.m.f. wave, by the use of reactance, could not always be made sinusoidal, and when this was accomplished, it was at the expense of greater generator capacity. This is undoubtedly due to the fact that a circuit can be tuned to but one frequency at a time, and when the third harmonic current was neutralized, the reactance allowed a very large fundamental to pass. The power factor is explained by the fact that the harmonic currents in cable tests predominate in the current wave, whereas the voltage is largely fundamental. The harmonics in the current wave contribute no power with respect to the fundamental voltage, yet all add up in quadrature, contributing to the volt-amperes.

These results show that in our particular case, at least, a shunt reactance would be of but very little value in improving the generator wave form, and reducing the volt-ampere load of the generator.

Sine-Wave Generator

As a result of our tests, the wire manufacturer came to the conclusion that a generator of the ordinary design was wholly un-

suited for reliable testing of wires and cables. Moreover, no manufacturer would guarantee a generator to produce an approximate sine wave under these severe conditions of test. The services of Prof. C. A. Adams of Harvard University were secured, and under his specifications such a generator was built and installed, rated at 85 kv-a. All oscillograph records, taken up to the present time and under various conditions of test, have failed to show any departure from a sine wave.

The 50-kv-a. transformer has been replaced by one rated at 75 kv-a., 75,000 volts, operating at a much lower core-density than the former, and taking a much less distorted exciting current. Hence the distorting influence of this current on the generator wave is much less than it was in the case of the 50-kv-a. transformer.

Method of Measuring Voltage

It is essential to obtain reliable knowledge of the maximum voltage to which the cable may be stressed under the preceding conditions of distorted wave form, if the tests are to be of any great value. Where the wave varies from a peaked to a flat-topped wave, the effective value is only a poor indication of what the maximum voltage may be. The circuit conditions are a function of so many variables that only a wide experience with his apparatus enables an operator to know what wave form may be expected under any given set of conditions.

The spark gap immediately suggests itself, as a means of determining these peak values. Although the needle gap is not conceded to be a device of high accuracy, it is accurate enough for the work in hand. There are objections to its use, however. The voltage can only be determined by connecting the gap in parallel with the cable to be tested, and noting the transformer primary voltage when the gap breaks down at the predetermined value at which it is set. This is a very dangerous practise, as a disturbance is created in the highly oscillatory circuit already described, and cables have often been known to puncture at a voltage apparently much less than their rating, and after the gap had actually broken down. The spark gap can therefore be used only with considerable care, and the danger of a surge is always present. Furthermore, it is not a piece of apparatus that is easily or quickly manipulated, and is wholly unsuited for a testing room where a large number of tests must be completed in a short time.

The oscillograph in its ordinary form is a very satisfactory

FIG. 20 [MIDDLETON AND DAWES]

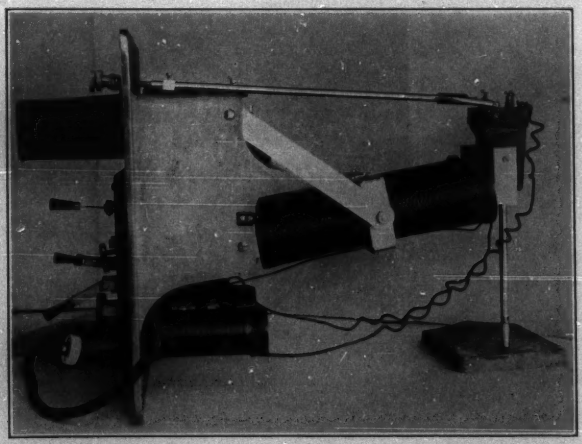

FIG. 21 [MIDDLETON AND DAWES]

piece of apparatus for experimental work, but it requires considerable attention, is clumsy to handle, requires skill to manipulate, and it does not hold its calibration for any considerable time.

Prof. F. A. Laws of the Massachusetts Institute of Technology, and the writers, have, however, adapted the oscillograph principle to an instrument which may be placed directly on the switchboard, and from which the peak value of any voltage wave may be quickly and accurately determined. A sectional view of this instrument is shown in Fig. 19, and is almost self-explanatory.

The lamp, having a straight tungsten filament, is mounted so that its distance from the vibrator may be adjusted to suit the optical requirements of the system. The light then passes through

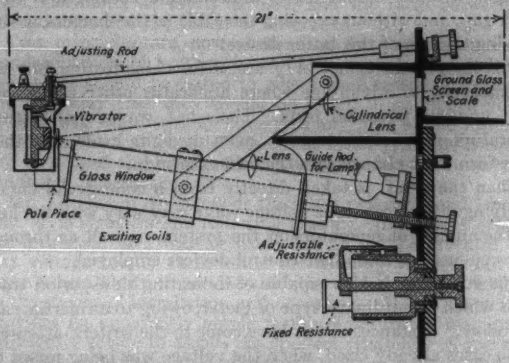

FIG. 19—SECTIONAL VIEW OF SIMPLEX VIBRATING VOLTMETER

suitable spherical lenses to the vibrator, from which it is reflected through a cylindrical lens to the ground glass screen, where the peak of the voltage wave may be determined from the extremity of the band of light.

The necessary vertical and horizontal adjustment of the beam of light can be made from the front of the switchboard by means of two milled heads which actuate the two adjusting rods. To compensate for changes in the amplitude of vibration due to variations of temperature and other causes, an adjustable rheostat is connected in series with the vibrator, and by throwing the vibrator circuit on direct current, with a double-throw switch, the calibration can be quickly and accurately made. A double scale is also provided. The magnets are operated at high satura-

tion, so that fluctuations in exciting current affect the instrument but slightly. The instrument as used, is connected to the secondary of a potential transformer, whose primary is connected directly to the high-tension circuit. Other views of the instrument are shown in Figs. 20 and 21.

To the manufacturer the importance of this type of instrument is evident. He is aware of the maximum stress at which his cables are being tested at all times, regardless of generator and transformer wave-form. No additional factor of safety is necessary in the cable due to uncertainty on this point. Furthermore, purchasers and inspectors can be quickly and convincingly shown that their cables are being tested at the specified voltage, without employing a troublesome oscillograph or a spark-gap, and without exposing the cable to the dangers accompanying the use of this latter device.

This instrument is not only useful for cable-testing, but can be employed to advantage where apparatus other than cables must undergo potential tests. The e.m.f. waves of all testing-generators are not sinusoidal, even at light loads, and their wave-form may change with the field excitation.

When the e.m.f. is taken directly from a commercial circuit supplying other loads, this voltage wave may vary with the load and the number of generators on the system, as well as through the compensators and other control devices employed.

This voltmeter is also capable of indicating slow-period transients which the ordinary type of meter, owing to its inertia, cannot follow. Instances of this have come to the writers' attention in the cases already cited, when the voltage was being raised on a cable. In a certain power system, it was found necessary to change the lightning arresters from 2300 to 3300 volts owing to the fact that continual discharges were taking place due to a considerable length of submarine cable having been added to the system. Whether this was due to a change in wave-form or to surges, the writers are not prepared to say, but such an instrument would have quickly given the required information.

In closing the writers wish to express their thanks to Prof. F. A. Laws, of the Massachusetts Institute of Technology, for his part in the development of this instrument; to Mr. W. G. Wolfe, of Boston, for his assistance in developing the optical system; to Professors C. A. Adams, H. E. Clifford, and A. E. Kennelly of Harvard University, for their helpful suggestions and criticisms during the preparation of this paper.

DISCUSSION ON "VOLTAGE TESTING OF CABLES" (MIDDLETON AND DAWES), DETROIT, MICH., JUNE 25, 1914.

W. A. Del Mar: The factor of safety of an insulated wire or cable, being the ratio of the breakdown voltage to the normal operating voltage, cannot be determined experimentally without testing the insulation to destruction. It can, therefore, never be definitely known in practise, although susceptible of approximate predetermination in the absence of faults, by calculation based upon tests. If, however, we define the *factor of assurance** of an insulated wire or cable as the ratio of the test voltage to the normal operating voltage, we can provide an experimental basis for the comparison of voltage tests. Thus, if a cable for operation at 11,000 volts is tested at 25,000 volts, we have a factor of assurance of 2.27. If the breakdown voltage is 75,000 volts, the factor of safety is 6.82, and the ratio between the safety factor and the factor of assurance is 3.0.

Two principles are now contending for recognition in the standardization of voltage tests. One is that insulated wires and cables should be tested to give a fixed factor of assurance, and the other that they should be tested to as high a voltage as they will stand without injury to any part of the insulation which may be free from defects. The latter principle is equivalent to a fixed and small ratio between the factor of safety and the factor of assurance.

Mr. Middleton recommends the latter principle, and I believe that he is right for the following reason: If a defect exists in the insulation of a wire or cable it may not be revealed by a test voltage two or three times the working voltage, but may cause a breakdown in service after the cable has been subjected to the strains of installation and operation. Hence a test which provides an apparently ample factor of assurance may not be sufficiently severe to assure the greatest reliability of operation. If, on the other hand, the breakdown voltage is calculated from the known dielectric strength of the insulation, a test voltage can also be calculated which will eliminate defects without injuring those parts of the insulation which are free from defects.

At high voltages, these two principles lead to the same results, as the thickness of insulation is usually proportioned to give a reasonable factor of assurance.

Working on the principle outlined above, the Wire and Cable Committee of the Association of Railway Electrical Engineers arrived at the following test voltages, which are somewhat lower than those given by Mr. Middleton. These test voltages are given in Tables I and II and Fig. 1, herewith. The difference may be partly due to the fact that most of the manufacturers have testing generators with less perfect characteristics than the one described in the paper under discussion.

*Proposed by Mr. F. J. White and incorporated in Standardization Rules of A. I. E. E., 1914.

The voltages in Table I were calculated by a formula similar to Mr. Middleton's except that the effective thickness of insulation was assumed to be slightly less than the nominal thickness, due to irregularities in manufacture and installation. An example of the former type of irregularity is the eccentricity of the insulation with respect to the wire, and of the latter, the reduction of insulation thickness on the outside of bends.

TABLE I.

TEST VOLTAGES, KILOVOLTS

FIVE-MINUTE TESTS

30 per cent *Hevea* Rubber Compound—Use 100 per cent of following voltages. Varnished Cloth—Use 75 per cent of following voltages. Impregnated Paper—Use 75 per cent of following voltages.

Size of Conductors.	Thickness of Insulation, 64th Inch.							
	2	3	4	5	6	7	8	10
18 A. W. G.	1.0	2.5	4.5	5.5	6.5	7.5	8.5	10.5
16	1.0	2.5	4.5	5.5	6.5	7.5	8.5	10.5
14		2.5	5.0	6.0	7.0	8.0	9.0	11.0
12		2.5	5.0	6.0	7.5	8.5	9.5	11.5
10		3.0	5.0	6.5	8.0	8.5	10.0	12.0
8		3.0	5.0	7.0	8.0	9.5	11.0	13.0
6			5.0	6.5	8.5	10.0	11.5	14.0
4			4.5	6.5	8.5	10.0	11.5	14.5
2			4.0	6.0	8.0	10.0	12.0	15.0
1			4.0	6.0	8.0	10.0	12.0	15.5
0				5.5	8.0	10.0	12.0	15.5
00				5.0	7.5	9.5	11.5	15.5
000				5.0	7.5	9.5	11.5	15.5
0000				4.5	7.0	9.0	11.5	15.5
250,000 cir. mils				4.0	6.5	9.0	11.0	15.5
500,000				2.5	5.0	7.5	10.0	14.5
750,000						6.5	9.0	14.0
1,000,000						5.5	8.0	13.0
1,250,000							7.5	12.5
1,500,000							7.0	12.0
1,750,000							6.5	11.5
2,000,000							5.0	10.5

(For intermediate sizes use the voltages corresponding to the next larger size, having the same thickness of insulation.)

TABLE II.

TEST VOLTAGES, KILOVOLTS

		Thickness of Insulation, 64ths Inch.								
		12	14	16	18	20	22	24	26	28
6-5 A. w. g.	Rubber	16	18	20	22	23	25	26	28	29
	V. C. or Paper	15	17	19	21	23	26	28	30	31
4-2 A. w. g.	Rubber	17	19	22	24	25	26	28	29	30
	V. C. or Paper	15	17	20	23	25	28	30	32	34
1-0000 A. w. g.	Rubber	18	21	23	25	27	28	30	31	32
	V. C. or Paper	16	19	22	24	27	30	32	34	36
250,000 cir. mils and larger	Rubber	19	22	24	26	28	30	31	33	34
	V. C. or Paper	17	20	23	25	28	31	33	36	38

While the logarithmic formula is useful in calculating the test voltage for a given size of conductor and thickness of insulation, it is dangerous for calculating the thickness of insulation for a given working voltage, as mechanical considerations generally dictate the use of more insulation at low voltages than is indicated by considerations of dielectric stresses. The requirements of the National Electrical Code for wire insulated for 0 to 600 volts represent the results of experience as to the minimum thickness of insulation which has been found necessary in practise. The thickness should seldom be less than required by the Code and should sometimes be more, regardless of voltage.

It should be noted that the formulas given in this paper do not take into account the difference in dielectric stress due to the size of strands in the cable. This has been treated by Prof. Levi-Civita in a paper by E. Jona in the Transactions of the

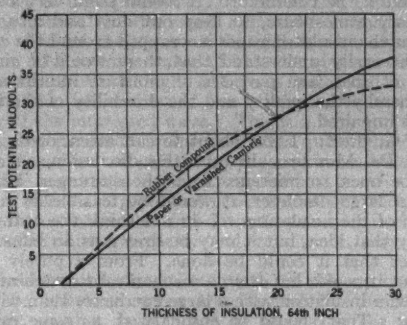

FIG. 1

International Electrical Congress, 1904. It would be interesting to hear whether Mr. Middleton's experiments agree with Prof. Levi-Civita's calculations.

I regard the paper by Messrs. Middleton and Dawes as one of the most important that has ever appeared on this important subject and believe that it will exert a strong influence in the rational standardization of voltage tests of wires and cables.

C. O. Mailloux: On the second page the authors speak of paper as an insulation for wires and cables. There is a third method of making high-tension cables, which consists in wrapping the conductor with a previously prepared paper. The paper, which is first treated with an insulating compound, is wrapped into rolls; and then the conductor strand from which the cable is to be made is wrapped around with this treated paper to the proper thickness, after which the cable covering

is placed on the whole. The cable is then submitted at once to the proper test. The process is shorter and simpler, and less expensive than the other processes of preparing the cables with dry paper, subjecting them to a vacuum, and then treating them with compound. There is an English firm which makes high-tension cables according to that process. I understand they have given satisfactory results, though I am not informed as to the comparative results. It would seem that if the method lends itself to the preparation of insulated cables for high tensions, and if such cables can withstand high tensions, the process would have some advantages: One could make sure more easily that every portion of the insulating material would be properly treated with the compound, and also that all of the defective parts of the insulating paper were eliminated or removed. On the other hand, there is the difficulty resulting from the possibility of entrained moisture at the time of laying the insulating paper around the conductor. It would seem very difficult, in an ordinary atmosphere, to keep out dust and also moisture, so that, as the insulated paper is wrapped around the conductor, one might easily understand that there would be air bubbles, particles of dust, and particles of moisture imprisoned in the cable, whereby the quality and the durability of the insulation would be impaired.

Henry G. Stott: I was about to call attention to the point that Mr. Del Mar brought up in his discussion, which is that it may be open to inference from the statement here that if there is a large diameter, it would be feasible to reduce the thickness of the insulation. I do not think the authors desire to convey that idea, but it may be drawn as an inference from this paper that it could be done. From a purely electrical standpoint it could, but from a mechanical standpoint we must have heavier insulation with a large conductor than with a small conductor. That should be emphasized, as some might take advantage of the curve to say that they could reduce the insulation on 500,000-cir. mil cable, but if they did so, they would get into trouble later on.

On page 1193, at the bottom of the page, is a paragraph on over-stressing cables. That is a point we have heard a great deal about in the last fifteen or twenty years. We have had in use now several hundred miles of cable over 15 years. These are all high-tension cables, and they are put under tests at 2.5 times working potential once a year. There is not the slightest sign of deterioration in the cable, after fifteen years' use. In fact, some of these cables were originally designed for use on 6600 volts, and are now being used on 11,000 volts, and in spite of this we have had this 2.5 times pressure test on them once every year, and many of them have had it as many as eight or ten times a year, due to cable changes, etc. Each time the cable is cut for any purpose, it receives the breakdown test, and once a year on general principles it receives a breakdown test.

We should prefer to have the cable break down on test, rather than in practical operation. While theoretically there may be some result of over-stressing of cables, yet practically, based on fifteen years' experience, with many hundreds of miles of cables, we have not yet found that to be so.

E. E. F. Creighton: I should like to ask Mr. Middleton something of the theories—he said there were many—to explain why a short piece of cable will stand so much more potential than a longer piece.

Charles L. Fortescue: I want to call attention to the very common mistake in attributing the third harmonic distortion of the transformer to the hysteresis. The distortion in the transformer is directly due to the cyclic variation in permeance, a small part of which is caused by hysteresis. Hysteresis produces no distortion.

In connection with the proposed method of measuring maximum voltage of high potential, Mr. Chubb and I at last year's mid-winter convention described a method of measuring the maximum value of the wave on the high-tension side, using a condenser. The average value of the charging current of the condenser across which high voltage is impressed is directly proportional to the product of the maximum voltage and the frequency of the impressed wave. This is a very simple way of measuring the maximum value, and it is quite reliable. I do not think a method of measuring the maximum value of the wave which requires a voltage transformer is reliable. The fact that a sine wave generator is used does not prevent third-harmonic distortion in the step-down transformer itself, which, due to its distributed capacity and inductance, may be quite large.

The third-harmonic distortion due to the step-up transformer will also be enhanced when transformed by the step-down transformer, so that as a means of measuring the maximum of the secondary voltage of the step-up transformer the proposed method will not lead to correct values. It is better to measure the maximum value directly by the method we have described or else by some modification, such as that described by Dr. Whitehead in his paper presented yesterday (*The Electric Strength of Air—V*).

Some question has been raised as to why long cables break down on test more easily than short cables. I think this is due to the combined effect of the distributed capacity and self-induction of the cable. When the voltage is supplied to the end of the cable, which is usually coiled on a spool, the actual average voltage in the cable, in the case of a long cable, is much higher than the voltage at the end, due to the effect of distributed capacity and inductance. It may, in long cables, be 15 or 20 per cent higher at the end of the cable than at the point where the voltage is applied. I think this may possibly be the reason why a long cable breaks down more easily than a short cable.

Percy H. Thomas: I will ask Mr. Middleton a question. He has discussed the effect of the third and other harmonics on the maximum voltage which may be impressed on a cable. It occurs to me that there is another effect of the high frequency which may possibly be important, and that is its heating effect. The insulation of an underground cable is stressed severely. The alternating electric stress causes a certain amount of heating within the material. That heating at 60 cycles, we will say, is almost negligible. At 180 cycles, or 200 or 300 cycles, that heating may be very important. A third harmonic, or fifth harmonic, so located with regard to the fundamental as to reduce the voltage peak, might develop heat enough within the dielectric, especially at any peak point, to raise the temperature to the puncturing point. I would like to know if anything has been done along that line of investigation.

The other question is about the puzzling fact that a long cable apparently breaks down at a lower voltage than a short cable. I would like to see two tests made, one with an outfit such as described by Mr. Middleton, comparing a long length with a short length cable, and a second test comparing a long length with a short length of cable, made according to Mr. Stott's generator method. Tested by the former method, you might find a marked difference between the voltage of failure in the short and long length of cable. Tested by the large generator, on the other hand, you might find there was not so much difference. This matter of the distortion of the wave by the large charging current of the long cable with the possible introduction or magnification of the high-frequency harmonics, may mean that there is produced a high-frequency effect in the test of the long cable, which does not exist with the short cable.

J. R. Craighead: In respect to obtaining a voltage supply, a generator which gives a sine wave is the most satisfactory, provided it will maintain the sine wave under testing conditions, but as the author states, those generators are rather rare, especially when loaded on a capacity load of pretty near their limit.

There is an alternative way which consists in using any ordinary line potential of a normal commercial wave form, and with a sufficient power, so that the capacity effect on the line wave is absolutely negligible. If this is taken through a transforming outfit of considerable reactance, it is not difficult to obtain a wave which more closely approaches a sine than the line wave itself. This was tried out to some extent in the high-potential testing of large turbine generators, obtaining by the oscillograph the wave forms on the high- and low-tension sides of the step-up transformer, and also the line wave, back of the regulating apparatus. For most large capacities it is not very difficult to get the correct amount of reactance so that the wave form across the machine under test is satisfactory.

In regard to the voltmeter described, the use of the oscillograph for this purpose was described and the suggestion of an

elementary oscillograph-voltmeter was made in a paper by Mr. L. T. Robinson and Mr. J. D. Ball presented two years ago at the Boston convention, entitled *Permeability Measurements with Alternating Current.* (TRANS. A.I.E.E., 1912, Vol. XXXI, p. 1609).

W. I. Middleton: The point brought up by Mr. Stott and Mr. Del Mar is very well taken. We should possibly have mentioned the fact that we could not depart from the Underwriters' specification. We realize that the heavy conductor does require a thicker wall of insulation for mechanical purposes, and that we did not mention this specifically, was an oversight on our part.

In regard to the long and short lengths of cable, and the difference in their ability to withstand voltage strain and test, I too am looking for information. We had an interesting paper in New York last winter on the testing of cambric insulation with different size electrodes, and I must say that Mr. Farmer's experience with electrodes bears out my experience with the long and short lengths of cable. Further, some time ago there was a paper written, I think by Mr. Moody, on some corona tests, and it was then found that, with a short length of bare wire, corona started at a much higher voltage than it did with a long length. So apparently the same phenomenon occurs here as in other insulating materials, which, to my belief, breaks down the law of probability.

Mr. Thomas spoke about the long and short lengths of cable and also mentioned the effect of heating. We have tried to be very careful about this matter of heating, and so have recommended short period testing. Many tests require only one minute. We usually ask for five-minute tests, as we believe that this eliminates the question of heat. Then, again, these cables are generally submerged in water when they are under test, and the question of heating, under those circumstances, I believe, is almost entirely eliminated.

When a long time test is attempted a multitude of different factors are encountered, and the effect of ozone generated at the ends of the cable, which attacks the rubber insulation, gives rise to a lot of theories regarding the piling up of voltage on the ends of the cable, etc. We have tried to eliminate these factors in our regular practise, realizing that we are obliged to make many tests in the course of the day, and all of this work is carried out on commercial lengths of cable, as they pass through the test room of the factory.

Chester L. Dawes: In regard to Mr. Stott's remark as to the application of this formula to the calculation of the wall of the insulation, mechanical as well as electrical considerations must necessarily be taken into account. When the cable is once designed, the wall being of the proper thickness to take care of the mechanical and electrical stresses to which it will be subjected in service, the test voltage should be determined by this formula or one that is its equivalent, in order to be cer-

tain of breaking down any defects which may exist in the insulation.

As to Mr. Fortescue's remarks, I agree with him that the third harmonic is also due to changing permeability, but hysteresis necessarily represents changing permeability. If the iron could operate without hysteresis, the third harmonic might yet be present, of course.

The method which he suggests for measuring the peak voltage I admit is correct, but it must be remembered that a device to be used in the test room should be direct-reading and capable of being used and used rapidly by a testing room employee.

Referring to the distortion of the voltage wave through the potential transformer, we took one oscillogram on the primary of the step-up transformer, and another one on the secondary of the potential transformer, thus stepping-up and stepping-down, and we could discern no difference in the oscillograms.

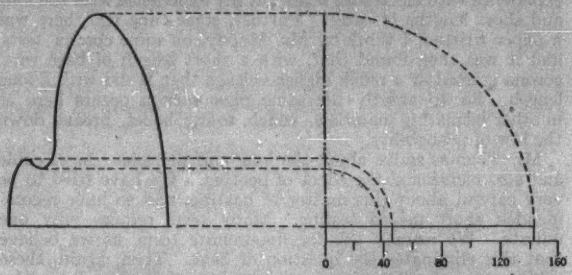

FIG. 2 FIG. 3

We had a very distorted wave under these conditions. Frequently we have looked into the oscillograph, without taking records, and have never been able to discover any difference between the wave form on the primary and that taken from the potential transformer secondary.

To have the voltage pile up in a long length of cable, inductance must be present. When the cable is installed, the inductance is very small, and, therefore, the probability of the voltage piling up is very slight.

In regard to Mr. Craighead's suggestion as to obtaining a sine wave with reactance, I assume that he means connecting the reactance in series with the transformer primary. This method could not be used in the test room, because it is too unstable a combination; and the operator would not readily understand how to adjust for a sine wave under each set of conditions. Further, resonance difficulties would be experienced, that is, the circuit might become sharply tuned, and a

high voltage might suddenly pile up on the cable. As I have just stated, it is necessary to have a method of measuring the peak voltage which the ordinary switchboard operator can understand and easily manipulate.

As to the voltmeter, I may add that a general idea of the wave form is obtained by observing the band of light. For instance, with a wave of the type shown in Fig. 2 (many of this type are shown in the oscillograms) the light on the scale will have the general appearance shown in Fig. 3. The light at the points corresponding to the lower peak and to the depression will be more intense than it is at other parts of the scale. In the same way, a flat-topped wave shows a much more intense light at the end of the scale than a peaked wave does. Similarly the tooth ripples are readily discerned.

Presented at the 31st Annual Convention of the American Institute of Electrical Engineers, Detroit, Mich., June 26, 1914, under the auspices of the Electrochemical Committee.

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STERILIZATION OF WATER BY ULTRA-VIOLET RAYS OF THE MERCURY-VAPOR QUARTZ LAMP

BY M. von RECKLINGHAUSEN

ABSTRACT OF PAPER

Mercury-vapor quartz lamps are applied industrially for the production of ultra-violet rays for the sterilization of water.

To obtain ultra-violet rays economically it is important to study the temperature of the luminous part of the lamp.

There are different ways for measuring the ultra-violet power, based on physical, chemical or bacteriological reactions. Such reactions are compared between them.

The paper refers to the historical development of mercury lamp water sterilizers and the development of pistol lamps for large sterilizing units.

Different germs are of different sensitivity to ultra-violet light.

It is important that the water should be clear when entering the sterilizer.

Description is given of two typical installations, one in Europe, one in America.

Data are given on the power consumption for the sterilization of water by ultra-violet rays.

WITHIN the last five years a new field for the application of electricity has been created in Europe based upon the electrical production of ultra-violet light for the sterilization of water and for other purposes. As this new industry is now being introduced into this country, it is of interest at this time to analyze its basis and principles.

The experimental and development work in this field has been done mainly in France, and prominently identified with it are the names of Courmont, Nogier, Henri, Helbronner, von Recklinghausen, Vallet and others. This paper deals particularly with the work done by the writer in collaboration with Messrs. Henri and Helbronner at the Physiological Laboratory of the Sorbonne University.

THE SOURCE OF ULTRA-VIOLET LIGHT

The only industrially-applied source of ultra-violet light is the mercury-vapor quartz lamp. The spectrum is known by its bright lines in the visible part and by a large number of typical

lines in the ultra-violet part, as shown in Fig. 1, which is drawn to proportional scale.

When starting this work we soon found that we had to go pretty fully into the question of the measure of the ultra-violet power of the different light sources at our disposal, so as to give the mercury quartz lamps the electrical characteristics which made them most useful for the creation of ultra-violet light. It is a well-known fact that the skin takes a less ghastly hue under the quartz mercury lamp than under the ordinary mercury-vapor lamp. Spectroscopic examination shows that this is due to a considerable increase of the intensity of the red lines in the spectrum of the quartz lamp. This phenomenon was examined somewhat more closely, with the following results:

An ordinary 110-volt lamp was taken, which normally operates at 3.5 amperes and 80 volts; it was operated at different wattages, obtaining thereby, naturally, different temperatures of the mercury arc. A spectro-photometric analysis was made of the five principal colors, composing the visible light of these lamps.

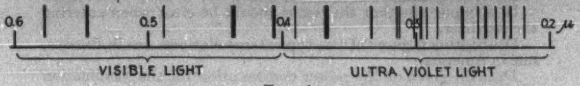

FIG. 1

Assuming the intensity of each color at the lowest wattage as unity, we note that increasing the wattage of the lamp tends to increase the red more than the other colors, as is shown in the curve, Fig. 2. It might therefore be expected that the increase of the ultra-violet rays with increasing temperature of the lamp, would be somewhat like the increase at the violet end of the spectrum, that is to say, proportionately less than at the red end. As will be seen from what follows, this is not the case. There is obtained, on the contrary, a considerably greater increase in ultra-violet than in violet rays with increasing temperature of the lamp.

QUANTITATIVE MEASUREMENT OF ULTRA-VIOLET LIGHT

The candle power standard for ordinary light is not a physical standard but a physiological one, being the effect on the eye of the sum of the visible wave lengths emitted by a defined source of light, produced by a defined fuel, burning in a defined way.

The eye not being sensible to ultra-violet, we only consider

the total *visible* energy sent out by this standard lamp. From the start it is therefore clear that if we want to define a standard of ultra-violet light we must do one of two things, namely: either define the standard in energy units (and wave lengths) or imitate our method of defining that standard of ordinary light and define our standard ultra-violet as the unit of effect produced by the ultra-violet rays. However, it is likely that the sums of such effects may be identical if *one kind of an effect is chosen* and may not be identical if another type of an effect is chosen.

The only true way of defining the power of the rays is by the analysis of the spectrum, and the determination of the energy

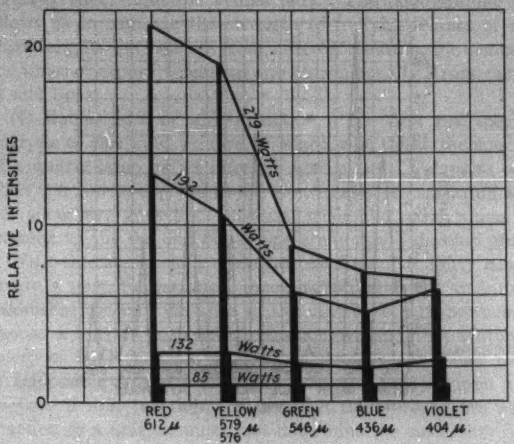

FIG. 2

sent out by each wave length. This method, however, is extremely inconvenient and, after all, does not give us what we want in practise.

It is therefore better to choose as a unit, some value of the particular effect which concerns the work in hand. If we want to follow chemical reaction under the ultra-violet light we choose arbitrarily as a unit one in which the desired reaction takes place in a defined way after a unit period of exposure to all the rays of the lamp. We may therefore say that for every type of reaction under the ultra-violet light we have to define a new unit of actinic power.

The different ways of examining the power of the ultra-violet spectrum are the following:

(1) Analysis of the distribution of energy in the spectrum. The way to measure this is to measure the amount of heat developed by a certain wave length, the measurements being made by means of a bolometer or thermoelectric couple.

Fig. 3 shows the distribution of energy in the spectrum of the mercury lamp as worked out by Ladenburg. Fabry has used different filters or screens to separate out different wave lengths. He finds that a 110-volt lamp burning at 27 volts, 3.5 amperes, sends out energy of which the distribution is as

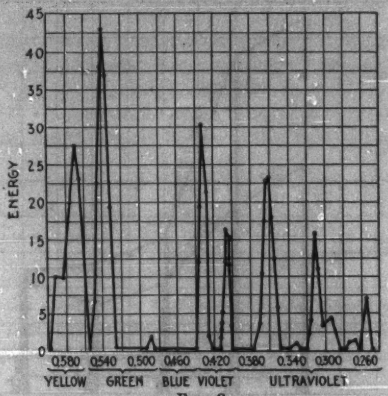

FIG. 3

follows: 93.7 per cent in the infra-red; 3.6 per cent in the visible spectrum; 2.2 per cent in the ultra-violet spectrum from 0.366μ to 0.313μ; 0.5 per cent in the ultra-violet from 0.313μ down to 0.253μ. As to absolute values, Fabry found that at one meter distance from the lamp, one square centimeter received 125 ergs per second of visible light and 76 ergs per second of ultra-violet light down to 0.253μ.

(2) Ultra-violet light falling on a condenser will ionize the air and this will be followed by a discharge of the condenser. This method could probably be used for analyzing the power of different wave lengths or for establishing an arbitrary standard of ionization by ultra-violet light.

(3) Many chemical reactions are produced to a greater extent by ultra-violet light than by visible light. The so-called Eder reaction of precipitation of calomel, which goes on very much faster under ultra-violet light than under visible light, is an example. The dissociation of gaseous hydrochloric acid and particularly the dissociation of silver salts may also be mentioned. The typical reaction of this latter kind is the blackening of photographic paper; this, for certain types of paper, occurs four times as quickly under a naked quartz lamp as it does under the same lamp with glass interposed, showing thereby that the ultra-violet part of the spectrum has a very much stronger effect than the visible part. The photographic plate allows us to compare the strength of individual lines of equal wave lengths but coming from different sources, by comparing the times of exposure necessary to obtain equally strong pictures of such lines.

(4) Bactericidal or abiotic action. The first real spectrum analysis of this kind we owe to Ward, who threw the spectrum of a quartz lamp on an infected agar plate. The parts of the plate which were exposed to the violet end of the spectrum would not show any growth of colonies, while the parts which were exposed to the red end of the spectrum would develop growth.

With the above-cited chemical reactions it is fairly easy to create a unit; for instance, precipitation of a unit quantity of calomel at the unit distance in the unit time. If, however, we choose a unit of bactericidal reaction, we find that cultures of microbes vary so much with age and other conditions that it is impossible to get sufficiently constant results upon which to base a unit reaction. If we wish, therefore, to use abiotic reaction as a unit we must first determine the sensibility of our reactive material, that is, the germ culture on hand, by exposing samples of it to the light of a lamp which is otherwise standardized. This means creating a laboratory-standard lamp which is so operated that it will always produce the same amount of ultra-violet rays.

The abiotic reaction which we chose as most convenient to handle was the measure of the exposure necessary to kill paramecias, these being similar to water bacteria and fairly easy to cultivate and to observe directly under the microscope, as they have a very violent motion when living and, naturally, no motion when dead. The method of procedure is to take a drop of such culture, expose it at a definite distance under the lamp, count

the seconds necessary to make them motionless, and compare the figures thus obtained with figures obtained under the standard lamp.

As the photographic paper method is infinitely more simple to handle, it was considered advisable to see whether it would not

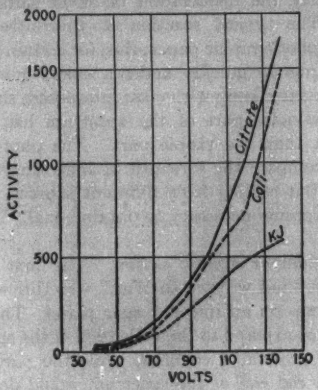

FIG. 4

correspond closely enough with the abiotic reaction to be a useful check upon the abiotic power of the quartz lamp. Fig. 4 shows the observations made simultaneously by the two methods, using a lamp operating at various voltages. Analyzing the results obtained by methods 1, 3, and 4 with lamps operating

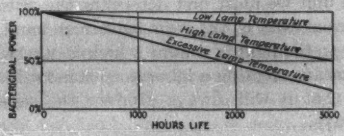

FIG. 5

at different temperatures (see Fig. 4), we may conclude that the relative increase in ultra-violet rays with increase in lamp voltage is considerably stronger than the increase for the green and blue rays.

Having found that we get more ultra-violet rays from a lamp

the hotter it is operated, we naturally had to take care not to overdo this and run the lamps at such a temperature that they would suffer thereby in their emission of light, particularly ultra-violet light. It is a well-known fact to everybody who has handled quartz lamps that at a certain temperature they will become almost entirely opaque to light, due to a kind of devitrification of the quartz which gives it the aspect of opaque glass. The maximum temperatures permissible so as to avoid this condition for the illuminating lamps had previously been determined. Some of our experiments for ultra-violet power were made with illuminating lamps which were operated at a somewhat lower wattage than usual. Fig. 5 shows the variation in abiotic action of such lamps, with time. The change, if any, was not very considerable.

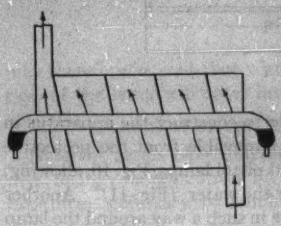

Fig. 6

On the other hand, Fig. 5 shows that lamps run hotter than illuminating lamps would lose considerably in their abiotic power with time. They evidently approach the limit at which complete opacity of the tube occurs. The problem is evidently exactly the same as for any type of incandescent lamp. We have to determine the working characteristics of the lamps to obtain the optimum of ultra-violet-time efficiency. It is probable that the electric characteristic of lamps for such work has to be chosen so as to obtain a somewhat lower temperature in the luminous part than lamps for illuminating purposes usually have.

Sterilizing Apparatus

The most efficient way for the mercury lamp to react upon water seems to be, *a priori*, to submerge the lamp entirely in the water which is to be sterilized, as proposed in 1906 by De Mare (Fig. 6), and tried in many experiments by Courmont and Nogier (Fig. 7). Direct contact, however, of the water with the heated lamp influences the luminous and ultra-violet efficiency of the quartz lamp to an enormous degree, as may be seen from Fig. 8. It seems to be certain, therefore, that it is better, if one wants to plunge the light source into the water, to protect the lamp from direct contact with the water, and this system has been adopted with modern apparatus. This protection against

direct contact can be secured by fusing over the lamp a wide quartz jacket which prevents contact of the light-giving portion of the lamp with the water, as shown in Fig. 9.

Difficulties, however, arose in the manufacture of such jacketed

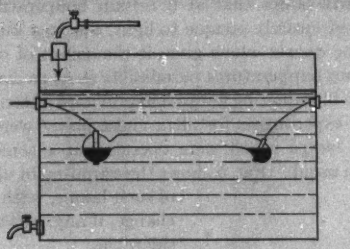

FIG. 7

lamps and it was found advisable to construct the apparatus in such a way that the lamp was removable from the protective jacket, as shown with the so-called pistol lamps, Fig. 10, allowing, nevertheless, all the light to enter the water (Fig. 11). Another method is to let the water circulate in such a way around the lamp

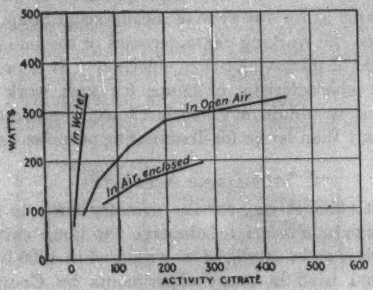

FIG. 8

that it would not come into contact with it, receiving nevertheless practically all the rays emitted by the lamp, as shown in Figs. 12 and 13.

Where it is more a question of convenience and less a question of efficiency the simplest method is evidently to place the lamp above the water but as close as possible to its surface. (Fig. 14.)

Figs. 15 and 16 show such arrangements which have been used on a large scale. Unfortunately, reflectors placed above such lamps have a low efficiency in reflection of ultra-violet rays. It

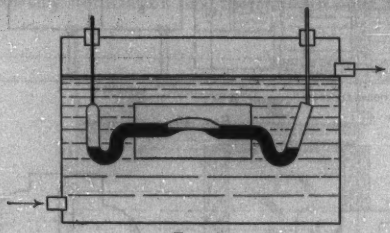

FIG. 9

may therefore be said that with such apparatus hardly half the rays of the lamp will enter into the water.

CONTACT OF THE RAYS WITH THE GERMS

Different germs have different sensibilities to the ultra-violet rays, as may be seen from Fig. 17, which indicates the relative exposures necessary to annihilate different germs under the

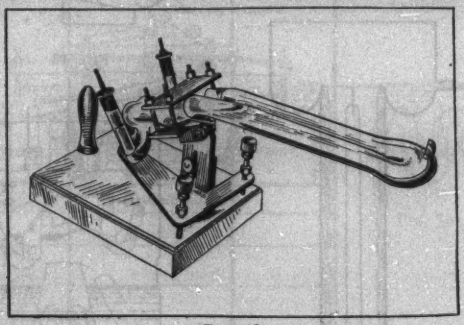

FIG. 10

same illumination. The ones of greatest interest to us are the water bacteria, and we find that they are killed in as short a time as 1/20 second, at a distance one to two centimeters from the powerful ultra-violet ray lamps. Water being practically as transparent as air to the ultra-violet rays, we are therefore certain that if a germ floats in the water it will be annihilated by

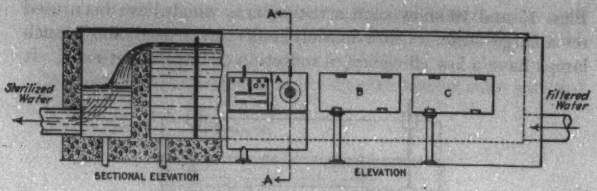

FIG. 11A

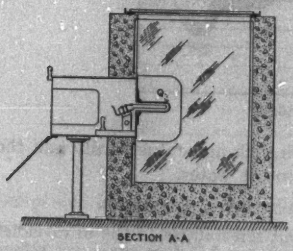

FIG. 11B

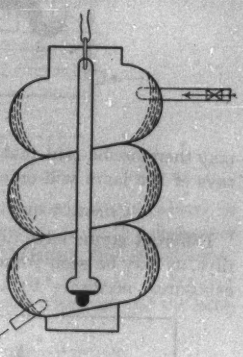

FIG. 13

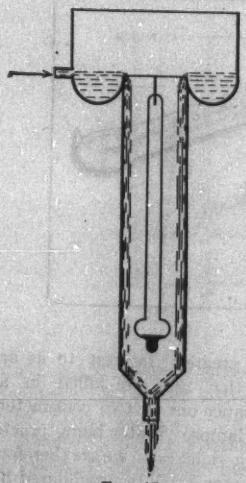

FIG. 12

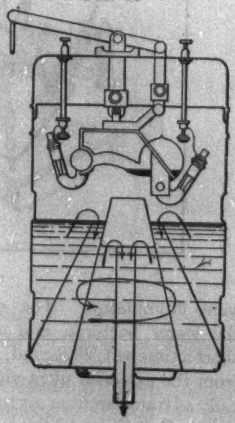

FIG. 15

getting into the illuminated zone, the condition for this being that no suspended matter is contained in the water which would form a shield for the germ.

Water for this sterilization has, therefore, in most cases to be

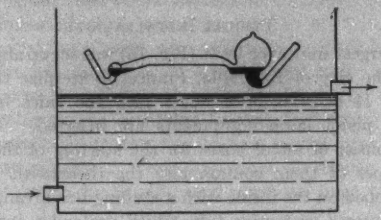

FIG. 14

filtered before being submitted to the sterilizing action of the rays. However, even very good filters will allow some microscopic matter to pass. It is much more effective, as shown by experiments, to stir up such water while it is going through the il-

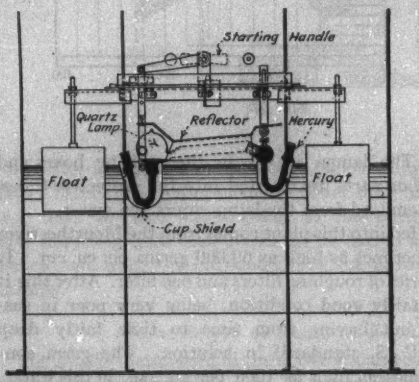

FIG. 16

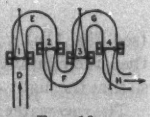

FIG. 16A

luminated zone so as to turn over and over any particles which otherwise might allow microbes to pass by under cover. The baffle arrangements as shown in Figs. 11, 15 and 16 are built in for this purpose of stirring up the water. For the same reason,

also, it is best to pass the water through several illuminated zones, which can easily be done by leading the water several times towards the same source of light (Fig. 15), or by passing it successively under several sources of light, as shown in Figs. 11 and 16.

Typical Installations

The largest unit ever built (Fig. 18) was set up about two years ago in the city of Luneville, France, to sterilize the city water supply. It consists of a flume into the sides of which ten 500-volt pistol lamp equipments are inserted. These equipments consist of metal boxes for the starting of the lamps (the latest types of them contain also the rheostats). The boxes are equipped on the inside with a stuffing box arrangement holding the quartz protective tube which protrudes into the water

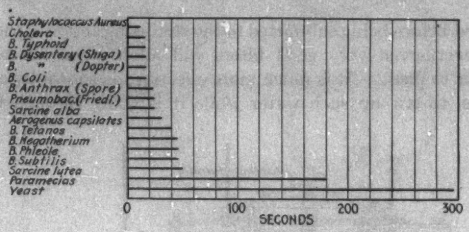

Fig. 17

(see Fig. 11B). The lamps are lit in the starting boxes and then their luminous parts are inserted into the protective tubes, so that the light emitted from the lamp enters the water.

The raw water fed into this plant comes from the Meurthe river and contains sometimes as high as 60,000 germs per cu. cm. It is clarified by a series of roughing filters and one filter. After this it is physically in fairly good condition, being very poor in suspended matter, but having from time to time fairly deep color (up to 45 U. S. standard) in solution. The germ contents are sometimes as high as 1000 per cu. cm. in this water. It is then passed through the sterilizing unit described above, coming under the influence of the light from one to two minutes altogether, according to the number of lamps running. This number (sometimes only 4) depends on the physical condition of the water, which is easily observed. The bacteriological tests of

the water when leaving the sterilizer rarely show more than 10 germs per cu. cm. and are often zero. Bacterium coli is always eliminated. Not only are the bacteriological tests satisfactory; the health of the community has improved considerably. Typhoid used to cause from 70 to 160 deaths annually; it is now practically eliminated, there being no cases at all this year.

Another typical installation was made in New York lately for the purification of the water of a swimming pool, which is naturally exposed to continuous pollution from the bathers. The water in this case is circulated continually through a filter to take out suspended matter and then it passes through the ultra-violet ray sterilizer. This apparatus is similar to the Luneville unit except for its size, as it contains only two 220-

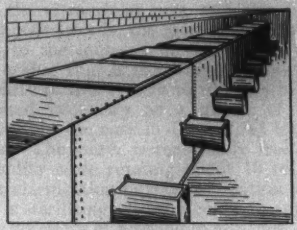

FIG. 18

volt pistol lamps. It is rated at 175,000 gallons capacity per day. Tests at the outlet of the sterilizer show only a few germs, and tests of the water going to the purifying apparatus have improved from 6000 germs per cu. cm. to about 350 germs per cu. cm. since the introduction of the ultra-violet ray apparatus.

CONSUMPTION OF ELECTRIC ENERGY

The smallest lamp used in the above apparatus operates at 110 volts with two amperes. The largest made so far is for 500 volts, 2.5 amperes. The largest apparatus built contains ten of the last-mentioned lamps. The power consumption in such a case, with a very large safety coefficient for the sterilization, is between 50 and 130 kw-hr. per million gallons of water. This amount of power is evidently not very great but it will

always do something to smooth out the load curve of a power station, as, in most cases, such apparatus will be operated continuously. Many installations of this kind have been made in Europe for both small and large water-works, and they are operating very successfully. Their simplicity and rapidity of action are highly satisfactory.

DISCUSSION ON "STERILIZATION OF WATER BY ULTRA-VIOLET RAYS OF THE MERCURY-VAPOR QUARTZ LAMP" (VON RECKLINGHAUSEN), DETROIT, MICH., JUNE 26, 1914.

Morgan Brooks: I notice one point, that is not of very great importance, that perhaps might lead to error. The author speaks of the light varying inversely as the square of the distance. That is true in the case of point source, but not true of line source. If the light is of any appreciable length in proportion to the tank, or the vehicle which is used in conveying the water, it will vary more nearly in inverse proportion to the distance, which will make a difference in some cases.

Theodore A. Leisen: The question of water purification is assuming such an important aspect throughout the whole country that any system of this kind will be welcome to all engineers interested in water supply. There are a few questions I would like to ask in regard to the result; first of all, as to the effect of a certain degree of turbidity of the water on the results of sterilization through the ultra-violet rays, and also the effect of color in the water; in other words, the ratio of increased consumption of current due to the increase in the turbidity of the water. My reason for asking that is that the question will come up as to the applicability of this system to waters where filtering may not be considered necessary as a means of clarification. I think that is notably the case in Detroit, at least as far as my experience goes. The water is reasonably free from turbidity, the actual turbidity scale running about 10 to 30 parts in the million, and for clarification purposes filtration would not really be necessary if a sterilizing medium could be applied that would act without the necessity of filtering in advance. I do not know what the turbidities go up to here in certain times of storm, in the case of the lake water, possibly too high to apply it without previous filtering. The water here is free from color, so that the color question would not enter into the discussion, except as a general matter of information. Dr. von Recklinghausen has said that, unfortunately for the power plants, the amount of current is very small; of course, that acts inversely, as far as the water department is concerned—the less current we have to use for sterilizing purposes the better satisfied we are. Our interests are not always identical.

From the commercial point of view the ultra-violet ray method of sterilization will have to come into competition with the use of certain chemicals, notably, calcium hypochlorite, which is being used extensively at the present time, and used very successfully. If, however, we can substitute a system of the kind described here, it will be very well, for the reason that it does away with all legitimate objections to any mixture of chemicals into the drinking water supplied. The use of hypochlorite of lime will unquestionably produce satisfactory results, so far as elimination of bacteria is concerned. If it is used in too large quantities, it

is likely to impart an odor and possibly a taste to the water, which is objectionable, and from the esthetic point of view, if from no other, the ultra-violet ray would be far more satisfactory than the hypochlorite of lime, but, from the commercial point of view, one must compete with the other, to a certain extent; and it would be very interesting from the water-works man's point of view, at least, to get some definite figures as to the actual cost per million gallons of water sterilized by means of the ultra-violet rays.

I believe that almost any city would be willing to spend a little more money in the cost of operating a plant to sterilize the water by means of ultra-violet rays than it would to sterilize the water by means of hypochlorite of lime, or any other chemical agent, but if the difference is too great, it is always going to be a question which system will be adopted. Here in Detroit the question will come up for consideration very soon. The matter of filtration has been discussed more or less during the last few years, and I assume that one of the problems which will devolve upon me to settle is whether we are compelled to put in a filtration plant or not. If we could substitute a system of the kind described, in place of the filtration plant, it would be a great advantage to the city and probably result in considerable economy. If the filtering plant is necessary in the first instance, it might be a question whether a sufficiently high degree of purity could not be obtained by filtering alone, without resorting to ultra-violet rays at all, although it is an admitted fact that no filtering gives absolutely pure water. On a percentage basis, we can show beautiful results, and on a practical basis we show good results. The average mechanical filter, assuming aluminum sulphate or sulphate of iron is the coagulating medium, will in almost every instance give a reduction of from 99 to 99.9 per cent, which is almost as near absolute purity as you are likely to get under ordinary conditions. The chart referred to here, showing the reduction in typhoid fever cases, is an interesting one, and one along the same line was shown by us. I would like to ask whether during the preceding years, 1908 to 1912, filtration alone was in use in that city, or whether they used raw water—in other words, when the filter plant was first started, in distinction to the time when the ultra-violet ray system was started.

If Dr. von Recklinghausen can give any figures as to cost, I am sure they will be very interesting to everybody concerned in the subject of water supply.

William B. Jackson: I wish to ask whether the sterilization by the ultra-violet ray does not come into direct competition with the sterilization by ozone, the same as it does with sterilization by chemicals; and if so, whether Dr. von Recklinghausen can give us any idea as to the relative cost of sterilization under the two conditions of operation. I would also be interested to learn whether there is any definite understanding of the physiological effect of the ultra-violet rays upon the germs, that is,

whether the germs are supposed to be killed by heat or poison, or what the effect may be.

M. von Recklinghausen: Regarding the variation of the power of light, I can state that the law of the square of the distance holds about true, although some absorption of light in the air has to be added, also correction has to be made for the line shape of the lamp.

To the interesting remarks of Mr. Leisen, who is one of the foremost water experts in this country, I would like to reply as follows: If turbidity consists of particles which are bigger than a microbe, it might shield the microbe. If turbidity particles are smaller than the microbe—for example, as in the case of the Mississippi water—I do not think they will shield it. I think that such very fine turbidity will act like a color in solution, that is to say as an absorbent, and reduce the abiotic action, at a certain distance, to a certain degree, which can be determined very closely. In my experience, very fine so-called colloidal clay in water acts just like color in water. We have worked with such turbidities up to twenty parts per million, and have had about as good sterilization in that case as in working with low turbidities.

This was worked out in a very small plant, so I am unfortunately unable to indicate the amount of power which this amount of turbidity would need on a large scale. If turbidity consists of coarse suspended matter, I believe it will depend on the size and character of this suspended matter whether it will handicap sterilization or not. It will surely shield some microbes, but it is most likely that these microbes, due to the stirring action of the sterilizer, will at some other moment not be shielded when passing through the illuminated zone, and will therefore be killed.

Let us take another case, of very heavy particles—suppose we take the effluent from a sewer; it is most likely that visible particles flowing in the sewer water will themselves be full of microbes and heavily infected inside. I think it is out of the question that the rays will strike, during a few seconds' exposure, the microbes hidden in the inside of such particles, and I think, that, *a priori*, heavy floating particles handicap sterilization if those particles are themselves polluted and contain germs. The light must be able to strike the microbe at its first, second or third, etc., passage through the illuminated zone. If that microbe is hidden every time it passes through the light it is not killed.

I understand that here in Detroit the turbidity of the water which is taken from Lake St. Clair right near Belle Isle is usually pretty good and does not show turbidity much higher than 10 most of the year. I understand that, however, during certain storms, the silt at the bottom of Lake St. Clair, which is pretty shallow, is stirred up and the turbidity is very high—I am not sure of the figures, but understand it is 250 parts per million—

that it is practically like coffee. I am certain that such water could not be directly treated with ultra-violet rays, because they would penetrate only a few millimeters, and after that they would surely be held up by either one or the other of these particles. Therefore, I think in a case like Detroit it seems to be necessary to filter the water at least during some months of the year, but possibly during ten or eleven months it need not be done.

Now, as to the question of competition—and this will be partly in reply to Mr. Leisen's question, also—I know that hypochlorite of lime is used to disinfect the water, and I think it will always be a little cheaper to take a barrel of hypochlorite of lime and stir it up with water, and drop it into the drinking water. I have no doubt about that, but you must consider that in the case of a waterworks plant, particularly a small waterworks plant, you cannot do this unless you have a chemist, or some expert, following the matter of addition of these chemicals to the water right along very carefully, so as to avoid giving the water a bad taste or imparting an odor to it. I think that you will find the application of these disinfectants will come pretty high if you include the amount of intelligent labor necessary to follow such applications. Besides, we have to consider the objection on the part of the public to the use of obnoxious chemicals in its drinking water.

In reply to Mr. Leisen's remarks regarding the cost of treatment per million gallons, it will depend on the original condition of the water. The waters which I have seen coming from the modern mechanical filters are of such an ideal physical purity, that is to say, there is such a decided absence of suspended matter and color, as I have never seen in waters in Europe. If the physical condition of the water is as perfect as this, I am persuaded that—although, of course, I could not say I could guarantee it—it would be hardly necessary to use more than 30 kw-hr. per million gallons to do the work, and if you use 50 kw-hr. per million gallons, as I stated in the paper, you have a safety coefficient which I think it is desirable and even imperative to have in hygienic work. I do not know what a kilowatt-hour can be made for, but call it one cent, then 30 cents per million gallons would probably be sufficient. There is another expense to be considered—that the lamps have to be renewed from time to time. I doubt if this will come to more than just the same sum, so that I think the total cost would be about 60 cents per million gallons. Now, in the case of chemicals, with all the intelligent supervision, etc., the cost may be a little less, but, as Mr. Leisen said, I do not think it is a question merely of dollars and cents, but a question of giving decent water to the public, and even if the total cost should run a few cents higher, I do not think a modern city would hesitate to do something for the welfare of the people and deliver always decent water.

I have not yet been able to get a plant running in this country in connection with one of these modern mechanical filters, which

give, according to my laboratory tests, such ideal and perfect conditions. It may be, therefore, that the figures of consumption I give are somewhat exaggerated.

Regarding the typhoid records in Luneville, France, up to 1911 they used spring water, without purification. In 1912 they started to filter the Meurthe River water, and added spring water to it, using practically 90 per cent of the river supply, and there was some falling off in typhoid cases at that time, as you see from the chart, due to the mere filtration of the water, at the rate of seven million gallons per acre, with some previous roughing. The fact that the typhoid cases have gone down to zero, since sterilization was applied, I think is due to the fact that sterilization does not let any coli, the indicator of germs of intestinal diseases, get through at all. I know that hygienic statistics have to extend over ten years to be really reliable, and you have to get statistics from many places. I am sorry that our industry is too young to give ten years' tests, and I can only give you those which I have at my disposal.

I have another case of a small plant which I showed you on the screen, where the same results were obtained; typhoid is prevalent all around that country, which is a suburb of Rouen, France. All round they used the same kind of water, and there was a good deal of typhoid in that district. Since the sterilizing plant has been put in there has not been a case of typhoid for two years—as the statement, which I have from the Health Office of the town, shows.

Now we come to the question of competition from another source—ozone. Ozone has not been used much in this country. It has been used to a certain extent in Europe to act as a sterilizing agent, and I think difficulties are encountered, not so much on the question of whether ozone sterilizes or not, but on the question—Do you produce ozone or do you produce something else? It is known that a slight amount of humidity in the air which is subjected to the ozonator, will produce something else than ozone, namely, nitrous acid, which is not a sterilizing agent, and therefore the results of the plants which are in actual service prove rather discouraging from the bacteriological point of view. From the economy point of view, I would only refer to one set of tests, which were made by the Aquedotto Nicolai in Genoa, for about six months. This trial plant supplies about a thousand tons of water per day, and the water was treated alternately by ultra-violet rays, and by an ozone plant. The current consumption was practically the same with the ultra-violet rays plant and the ozone plant, but in the latter case only so far as the ozonator was concerned, not counting the cost of moving the water to the ozonator and the cost of forcing the ozonized air through the water. Taking it altogether, I think the power used is less with the ultra-violet rays. In the case mentioned, the report says that the ultra-violet rays can be run by a little girl, while the ozone plant needs an engineer.

William B. Jackson: What is the relative first cost of the plants?

M. von Recklinghausen: I cannot tell you the relative cost of the plants, as I do not know the cost of the ozone plant. I know in this case—I suppose they are all different—the original cost was 2.5 times as much, but I do not know whether that would account for all costs. I do not want to give that figure as the real figure. What is needed is the machine necessary for ozonizing, the high-frequency alternator, high-frequency transformer, and then the maintenance of the dielectrics, which blow out from time to time, etc.

William B. Jackson: Does the ozone work better on muddy water?

M. von Recklinghausen: There is one thing strange about practically all sterilizing agents, and that is that they all must be used only on practically clear water. In the case of ultra-violet rays, there is the physical necessity of having the rays strike the microbes. In the case of any chemical sterilization like ozone or hypochlorite of lime, you need much more of the chemical, in the case of the water being muddy, than when the water is clear. I think that is because some of the sterilizing—that is, the oxidizing—agent is used up by the organic mud, and you need much more ozone, etc., to penetrate into the organic matter than if such floating matter or even organic matter in solution is absent.

The last question asked was: what the real effect is. Like many biological things, we do not know. If you expose water for a long time to ultra-violet rays, you might get a slight amount of peroxidation therein. This so-formed disinfectant could not, however, account for the sterilizing action of the rays, owing to the short period of time that the rays act on the germs. The amount of hydrogen peroxide generated by the light shining on the water is perhaps one millionth of what would be needed to produce enough peroxidation to act as a sterilizing agent. If we submit a germ to the ultra-violet light and look at it under the microscope, after having exposed it for a long time, we find its plasma coagulated, therefore many will say that the action is coagulation of the plasma. After just enough exposure to ultra-violet light, however, the germs appear to be identical with living ones, except that their motility has gone. I think the exposure necessary, for instance, under the pistol lamp, to kill the bacteria, is one-twentieth of a second. I doubt whether you can make a complete chemical change in that microbe during that short time.

Alfred Herz: Is the microbe permanently killed, or only stunned?

M. von Recklinghausen: Permanently killed.

Alfred Herz: Any record of that?

M. von Recklinghausen: I need only mention the many tests made in Europe on plants for getting sterile water for

surgical work. They want water which has no microbes, and they make a very strict test, which consists in taking 100, 200 or 300 cu. cm. of the sterile water and mixing it with sterile broth. They put these samples under the most favorable temperature conditions for the microbes to develop. After several weeks, if the microbe contained in that broth has not developed, they come to the conclusion that it is dead, and such results have been obtained over and again with water which had been freed of its often very rich content of germs by short exposure to the ultra-violet rays.

A. E. Walden (communicated after adjournment): For nearly seven years the writer has been experimenting with ozone gas for sterilizing water, and for a shorter period with the ultra-violet ray, and noting the interest in the paper on the ultra-violet ray, as evidenced by the published discussion, believes that further information would be of value.

The sterilizer we are operating in Baltimore has a capacity of four million gallons daily, and has been operating more or less satisfactorily for several years. We also procured in Europe an ultra-violet ray sterilizer for experimental purposes, it being the first, in our belief, to be used for this purpose in this country.

Now, it should be stated that both the ultra-violet ray and ozone apparatus have distinct fields, but that ozone will do work that ultra-violet rays cannot do, with the knowledge we have of both today. The ultra-violet ray has no action on algae, or amorphous matter, or color, while ozone has, although both reduce bacteria. Again, ozone will purify water without previous filtration, while the ultra-violet ray, to be most effective, must have a water low in turbidity.

Ozone sterilizing apparatus, including roughing filter (for use during times of high turbidity), can be constructed for $6,000 to $7,000 per million, in 5 million gallon units or over, and the total operating cost will be approximately $2.50 per million gallons, or under, allowing for local conditions.

A question was asked by Mr. William B. Jackson as to the relative merits of ozone and ultra-violet ray on muddy water (high turbidity), and it may be said that ozone is far and away superior to the ultra-violet ray under this condition in so far as we have knowledge today, and that with the ultra-violet ray with a water having a turbidity greater than 10 the manufacturers will not guarantee results. However, our experience with this system shows that the rays will satisfactorily penetrate turbidities of 20.

The cost of the lamps is excessive, and they are very fragile and easily affected by handling.

To get back to European results by either method, I want to state that they cannot be applied to conditions in this country, neither are they correct as we require them.

I submit herewith a short table of results at our plant, which we can and expect to improve on in our proposed new plant.

Table of Ozone Results

STERILIZING THREE MILLION GALLONS DAILY

Bacteria removed.....73 to 99 per cent.

At the same time removing as follows:

	Algae	Amorphous Matter	Color
Maximum.....	79%	80%	15 to 45%
Minimum.....	9%	11%	
Average.....	40%	50%	

Requiring from 60 to 90 kw-hr., or 2 to 5 kw. per million.

TABLE I—RESULTS OBTAINED FROM OZONIZERS AT HERRING RUN UNDER VARYING CONDITIONS (3,000,000-GAL. UNITS).

Bacteria per cu. cm.			*B. Coli* presumptive test		Color (parts per million)			Turbidity (parts per million)		
Raw	Ozonized	% Removal	Raw	Ozonized	Raw	Ozonized	% Removal	Raw	Ozonized	% Removal
4300	31	99.2	*4/4	0/24	65	30	53.8	40	40	0.0
1800	53	97.0	4/4	0/24	25	18	28.0	12	12	0.0
2080	25	98.7	1/4	0/24	25	20	20.0	18	18	0.0
1810	31	98.7	4/4	2/24	25	16	36.0	18	18	0.0
2300	79	96.6	0/4	0/4	28	18	31.7	20	20	0.0
146	18	87.6	1/4	0/4	24	21	16.3	8	8	0.0

*4/4 = 4 positive presumptive tests out of 4 one-cu. cm. samples tested.

TABLE I—(*Continued*)

RESULTS OBTAINED FROM OZONIZING WATER, NOVEMBER, 1909.

	Bacteria per cu. cm.		*B. Coli*		Color		Turbidity		Alkalinity	
Date	Raw	Ozonized	Raw	Ozonized	Raw	Ozonized	Raw	Ozonized	Raw	Ozonized
Nov. 3	3200	12	4/4	0/8	20	14	18	18	25	25
" 4	2700	6	2/4	0/8	22	15	20	18	26	26
" 5	1960	6	2/4	0/8	25	17	20	20	26	26
" 12	1300	12	4/4	0/4	24	14	18	18	25	25
" 12	1300	18		0/4	24	14	18	18	25	25
" 12	1410	15		0/4	24	15	18	18	25	25
" 12	1390	16			24	14	18	16	25	25
" 13	1920	54	3/4	1/4	23	17	20	20	25	25

TABLE I—(*Continued*)

RESULTS OBTAINED FROM OZONIZING WATER, NOVEMBER AND DECEMBER, 1909.

	Bacteria		*B. Coli*		Color		Turbidity	
Date	Raw	Ozonized	Raw	Ozonized	Raw	Ozonized	Raw	Ozonized
Nov. 24	5100	*810	4/4	3/4	25	20	25	25
" 26	2520	*650	2/4	2/4	22	18	20	20
" 27	1800	*740	4/4	1/4	22	17	23	23
" 29	2420	9	1/4	0/8	20	8	18	18
Dec. 2	3680	6	4/4	0/4	18	10	18	14
" 3	1420	13					14	14
" 4	1100	4	1/4	0/4	18	10	16	16
" 7	1240	6	1/4	0/4	21	15	15	12

*The results on Nov. 24th, 26th and 27th show the effect of ozone on water containing a great amount of organic matter. During these days a piece of straw braid was suspended in the mixing chamber of the ozonizer. The braid was removed on the 29th, with the improved bacterial results indicated.

TABLE II—RESULTS FROM 3000-GALLON OZONE APPARATUS (DOMESTIC STERILIZER).

Bacteria per cu. cm.			*B. Coli*		Color			Turbidity			Oxygen required		
Raw	Ozonized	% Removed	Raw	Ozonized	Raw	Ozonized	% Removed	Raw	Ozonized	% Removed	Raw	Ozonized	% Removed
2460	26	98.95	present	not found	22	5	77.28	20	20	00.0	1.55	0.60	61.30
2800	12	99.58	"	"	30	15	50	40	40	00.0	1.40	0.85	39.19
1100	5	99.55	"	"	17	0	100	15	15	00.0	1.15	0.55	52.18
1270	6	99.53	"	"	35	15	57.15	15	15	00.0	1.47	0.85	42.18
1200	0	100	"	"	12	0	100	17	17	00.0	1.15	0.70	39.13
59000	680	98.85	"	"	65	40	38.46	400	400	00.0	3.75	3.10	17.34

TABLE III—RESULTS FROM 3000-GALLON ULTRA-VIOLET RAY APPARATUS

Bacteria per cu. cm.						Average efficiency	*B. Coli.*				Parts per million				Volts	Amperes
	Sterilized						Raw		Sterilized		Turbidity		Color			
Raw	1	2	3	4	Average		Tests made	Tests positive	Tests made	Tests positive	Raw	Sterilized	Raw	Sterilized		
450	2	0	0	2	1.0	99.78	4	0	16	0	20	20	22	22	80	4
580	7	4	6		5.6	99.04	4	1	16	0	14	14	16	16	80	4
1390	5	2	0	4	2.7	99.81	4	2	16	0	15	15	14	14	80	4
310	8	4	2	0	3.5	98.78	4	3	16	0	12	12	10	10	80	4
490	4	6	6	2	4.5	99.09	4	2	16	0	18	18	12	12	80	4
210	0	0	4	2	1.5	99.29	4	0	16	0	20	20	12	12	80	4
600	0	0	0	1	0.2	99.97	4	1	16	0	16	16	10	10	80	4
720	4	2	0	3	2.7	99.63	4	2	16	0	15	15	8	8	80	4

Rise in temperature on the case of the sterilizer directly above the lamp.

Time	Start	5 min.	10 min.	15 min.	20 min.	25 min.	30 min.	35 min.	60 min.
Degrees Fahrenheit	80	94	142	180	194	206	208	210	210

Regarding the ultra-violet ray lamp, the quartz tubes give good results at first but in a short time become defective, due either to failure of seal or to a film of oxide on the tube inside.

In European practise the current consumption with filters and an effluent of low turbidity is from 36 to 140 kw-hr. per million gallons, the filters passing from 90 to 120 millions per acre per day. Water that has a turbidity of 45 parts per million cannot be sterilized satisfactorily. The maximum depth of water which has been sterilized is about three feet, and if this is reduced to one foot the approximate time might be said to be reduced in proportion to the effect of light rays; in other words, if the lamps sterilize at a depth of one foot at the rate of one second, when the distance is doubled, or at a depth of two feet, the time of required exposure will be about four seconds, but may vary 5 to 10 per cent.

The time of exposure runs usually from 50 seconds to 1½ minutes, but where the effluent is very low in color and turbidity, as from mechanical filters using sulphate of alumina, a period as short as 10 seconds will answer for effective sterilization, but is not to be recommended for safety under operating conditions.

The life of the lamps is guaranteed at about 3800 hours, and in testing to see if the ray efficiency (consequently the bacterial efficiency) is maintained, it appears that the lamps are tested at a distance of 50 cm. with solio paper, and if the paper turns pink in approximately 10 seconds the lamps are considered all right, but if it requires 15 seconds, or more, there is some question

as to their efficiency and they are removed for further test. It should be noted that there is no satisfactory method devised for the control of the lamps in operation to tell accurately when any have deteriorated, and just how fast they are deteriorating, which makes operation uncertain, and the system will require more technical supervision for this reason.

We have had considerable trouble with lamps blackening, or mercury oxide.

There is no change in the organic matter, as there is with ozone, and as before stated, the time and depth will probably vary 10 per cent. The efficiency will be higher with the higher voltage lamps requiring 400 to 500 volts.

With ozone gas, climatic conditions affect the operation, although this has been practically eliminated; and then there are troubles from punctured dielectrics, the expense of renewing these, however, being small.

This gas will alone remove the major portion of the algae and organic matter; and reduce the color from 15 to 40 per cent, and at the same time remove from 73 to 99 per cent of the bacteria, but if the organic content is high the reduction is high and the bacteria reduction is lowered, but as we become more familiar with these conditions they will be removed or improved.

A test for ozone can easily be made, and an approximate determination of the strength made by passing a given quantity through iodide of potassium solution, and we have proved by many hundreds of tests that at no time has it been possibe to detect nitrous acid, and further, that the removal of the algae and organic matter causes the bacteria to die in the mains, and it is believed that this is due to the removal of the organic matter necessary to maintain bacterial life.

It might be stated that all forms of bacteria are really vegetable micro-organisms; also that there are some 60 gas-forming bacteria; and it is not possible to determine the *Coli* other than in a presumptive manner (except by special plating requiring a period of time too long for the purpose. We have further found, in testing for bacteria in air, that from one cu. cm. taken from a solution made from one square inch taken from the air filter and distilled water, there were 9000 gas formers, or presumptive *B. Coli*, out of a total of 27,000 bacteria, which goes to show, we believe, that ozone gas will eventually prove of value for air purification, as soon as its action and method of handling are better understood.

For those seeking further information on this subject there will be found papers in the *Proceedings* of the American Works Association of 1911, also papers by the chemist of the Baltimore County Water and Electr c Company, Mr. Sheppard T. Powell, in the *American Water Works Journal* of September, 1914, and also Dr. von Recklinghausen's paper of the same date.

It is our belief that both these sterilizing agents will find a field in both water and sewerage treatment, and particularly in

the treatment of the discharge from tanks of the Imhoff type, as evidenced by our experiments.

It may be added that the ultra-violet ray has recently been tried in Baltimore for sterilizing milk, and the result was that a decided offensive taste was imparted to the milk, which would prevent the use of this agent for this purpose. Further, milk sterilized with ozone will not give up the characteristic taste of the gas used, as it seems to be retained in the milk. However, rancid butter can be renovated without any apparent effect on the substance itself.

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A HIGH-SPEED PRINTING TELEGRAPH SYSTEM

BY CARL KINSLEY

ABSTRACT OF PAPER

The paper describes a system of high-speed printing telegraphy devised by the author, a prominent feature of which is the simplicity of the apparatus and its operation. The author briefly mentions a number of high-speed systems which have been tested by the operating companies, none of which have completely fulfilled all the requirements for accuracy, rapidity and low cost which are desirable for commercial work.

The system described is operated in connection with a commercial typewriter to which a punch is connected which perforates a half-inch strip of paper with groups of holes distinctly spaced in five rows, each group representing a letter. The punched strip of paper is then sent through the transmitter so that the holes pass under five wire brushes. Batteries of either polarity are thus connected between the earth and either one of a pair of conductors, or batteries of different potential can also be used. At the receiver there are five elements which are separately controlled and these elements make an autographic record by means of a local battery on a moving sensitized paper whenever they touch the surface. The apparatus, which is comparatively simple, is illustrated and described in detail. On the basis of simplex working and the use of two wires, the operating speed is 650 words per minute over a 375-mile line. If duplex working should be used the total speed of working per wire would be increased accordingly.

THE RATE of increase in the amount of business transacted by telegraph has been most marked during the past few years. The extension of the network of telephone wires and their universal use in local business has seemingly stimulated the desire for a formal method of inter-communication which is more rapid than the mails.

The operating companies have responded as fully as they could, with the means available, to the public demand for a more rapid, accurate and inexpensive service. They have carefully tested many systems of telegraphic transmission that have been presented to them. None of the systems, however, has fulfilled all of the requirements for accuracy in the transmission of the messages, rapidity of operation from the receipt of the message to its final delivery, and low cost; the latter includes,

in particular, interest on invested capital, depreciation of telegraphic apparatus and lines, maintenance of plant and cost of operation.

It is impossible adequately to mention in the brief space available the telegraph systems which have already been tried, some of which have by no means been discarded. Among them the following may be of particular interest.

The Rowland multiplex printing telegraph system[1] has enjoyed a limited use in Italy and was experimentally operated on commercial business for a considerable time in this country. On the basis of eight machines operating simultaneously over two wires a speed of 400 words per minute could be obtained.

The Murray printing telegraph[2] was given a commercial test in America in 1900 and later taken to England where it was developed to a much more perfect state in the laboratories of British P. O. Department. It has recently been given a month's trial in this country. Used duplex with four machines working on the two-wire circuit and with eight automatic translators, a speed of 400 words per minute can be reached.

The Baudot printing telegraph[3] has been extensively used in France and India, while recently its use has been spreading to Great Britain, where certain improvements have been added. On the basis of duplex working, and using two wires, 160 words per minute can be transmitted.

The Siemens-Halske rapid printing telegraph system[4] has been remodelled from the system developed and extensively tested about 1903, which used a photographic process of recording. In its present form it has been successfully used on certain German lines and is being tried over three or four different circuits at the present time. It seems to be specially suited for underground

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1. G. Robichon, "Le Telegraphie Rowland," *Journal Telegraphique*, Jan. 25, 1901 and Feb. 25, 1901.

Potts; *The Rowland Telegraph System*, A. I. E. E. TRANS., 1907, Vol. XXVI p. 507.

2. Vansize; *A New Page Printing Telegraph*, A. I. E. E. TRANS., 1901, Vol. XVIII, p. 7.

Murray; "Practical Aspects of Printing Telegraphy," Inst. Elec. Eng. *Jour.* v. 47, p. 450, 1911. See also *Electrician*, May 5 and 12, 1911.

3. "D'Appareils Baudot," Poulaine and Faivre, Paris, 1906.

Williams; "The Baudot Telegraph System in India," *Electrician*, Mch. 22, 1907.

4. Franke, "Der neue Schnelltelegraph der Siemens und Halske," *Elektrotechn. Zeitschr.*, Sept. 25, Oct. 2 and 9, 1913.

cable work, as the speed of each instrument is low and the required perfect control of both synchronism and phase of the transmitter and receiver is then not affected by atmospheric conditions. The necessity for an entire absence of disturbance can be comprehended when it is noted that many letters require the operation of seven relays to switch circuits in the through line in preparation for each record. On the basis of duplex working and the use of two wires a speed of 400 words per minute is obtainable. This is only half as fast as the early form which required the developing, fixing, washing and drying of the record of the receiving message and thus produced a condition at the receiving end which was considered uncommercial.

The Pollak-Virag writing telegraph system,[5] unlike any of the preceding, does not require synchronism between transmitter and receiver. The received message, however, is photographically recorded on a sheet, which process entails expense and delay in handling the message. It was given an extensive commercial test over German lines and also was exhibited in England and in this country in 1899. On the same basis as that used in the tests of the previous systems the Pollak-Virag telegraph operated at 650 words per minute.

The system about to be described does not employ synchronism between transmitter and receiver, there are no relays used in the operation at either end of the line, only one instrument is employed, and the message is received ready for distribution. On the same basis of computation used in the above systems the speed of operation of the author's printing telegraph is 650 words per minute over a 375-mile (603.5-km.) line.

Plan of Operation

The method employed is direct throughout and the transmitting and recording parts are capable of such adjustment that the speed of operation is limited only by the speed of the line. The mode of operation is as follows:

By means of a punch which is connected to a commercial typewriter a half-in. (1.27-cm.) strip of paper is punched with a

5. "Der Schnelltelegraph von Pollak und Virag", *Elektrotechn. Zeitschr*, Oct. 11, 1900.

"Recent Improvements of the Pollak-Virag Writing Telegraph," *Electrician*, July 3, 1903. "Telegraphie Rapide Systeme Pollak et Virag," *Ecl. Electr.*, Jan. 5, 1907.

series of groupings of holes distinctively spaced in five rows, each group representing a letter. The punched strip of paper is then sent through the transmitter so that the holes pass under five wire brushes. Batteries of either polarity are thereby connected between the earth and either one of a pair of conductors. Batteries of different potential can also be used, and in one case that is done, making five different transmitting impulses. Fig. 1 shows the wiring connections, a representative piece of transmitting tape, the printing elements and a section of the record.

At the receiver there are five elements which are separately controlled, except that No. 3, which needs only the normal current, also operates when the strong current needed to operate No. 5 is received.

The printing is accomplished by subdividing the alphabet

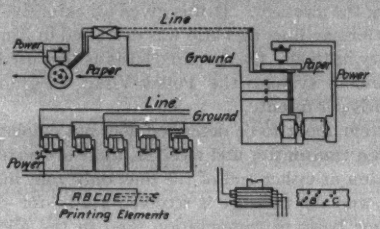

FIG. 1

into four independent elements and a fifth which, whenever used, accompanies one of the others. These elements then make an autographic record, by means of a local battery, on a moving sensitized paper whenever they touch the surface. It is merely necessary to have them operated in the proper sequence and with the desired interval in order to obtain any letter or figure of the alphabet.

PHOTOGRAPHS OF COMPLETE APPARATUS

Fig. 2 shows the punch for preparing the transmitting tape. A commercial typewriter is set on the punch base and the operation of preparing an office copy of the message also punches the transmitting tape. The depression of the digit bar sets the proper punch combination, then closes the circuit of an electro-

magnet which completes the operation of punching and spacing the transmitting tape. The tape is then rolled up ready for use on the transmitter. As many punching machines can be used at the same time as may be needed to supply the transmitter with a sufficient number of rolls of prepared messages.

Fig. 3 illustrates the automatic transmitter. The roll of paper carrying the message is driven under the wire brushes, which drop through the holes and make contact with the underlying rings, five in number. These rings are slowly rotating, driven by the paper friction, so as to insure a continually changing point of contact. No trouble at all has been experienced with faulty contacts. No speed control has yet been used on the driving motor as it has not been found necessary to have any exact speed of transmission.

Fig. 4 shows the method of construction of the artificial line, which needs more than a passing notice. It is made of a great many sections all connected in series. Each section consists of two tinfoil grids, separated by wax paper with solid tinfoil sheets outside of them, also separated from the grids with waxed paper. The solid sheets are 6½ in. by 9 in. (16.5 cm. by 22.8 cm.) and completely cover the grids, which are superimposed. There is thus complete distribution of the capacity and resistance of the two parts of the circuit with respect to each other as well as with respect to the ground, while each section is shielded from the neighboring sections. The total capacity from either line to ground, measured with an a-c. pure sine wave of 120 periods per sec., is 4.05 microfarads. The total resistance of each line is 747 ohms, while the leakage resistance due to dielectric absorption is 2×10^4 ohms. There is no appreciable self-induction. On the basis of an open wire circuit having a conductor 0.43 cm. in diameter, the capacity and resistance relation would make the artificial line equivalent to a circuit 375 miles (603.5 km.) long.[6] Since the open wire line has also distributed self-induction, the current at the distant end of the actual line would be greater than that at the end of the artificial line, if the impressed e.m.f. were the same. The equivalent length of actual line might be calculated in another way on the basis of an alternating current of equivalent frequency. When transmitting messages at the rate of 650 words per min.

6. NOTE—The above equivalence is obtained by interpolation in the table on p. 256 of "The Propagation of Electric Currents," J. A. Fleming.

the actual duration of an impulse is 1/720 sec. This would be equivalent to a frequency of 360 periods per sec.

$$\text{Assume } I_r = \frac{V_s}{Z_0} \operatorname{cosech} Pl \tag{1}$$

$$\text{Where } Z_0 = \text{initial sending end impedance} = \frac{\sqrt{r+jx}}{\sqrt{g+jb}} \tag{2}$$

$$\text{and } P = \text{propagation constant} =$$

$$\alpha + j\beta = \sqrt{r+jx}\sqrt{g+jb} \tag{3}$$

r, x, g and b are respectively the resistance, reactance, conductance and susceptance per mile.

I_r and V_s are the current at receiving end and impressed e.m.f. at sending end.[7] With the same V_s the I_r will be the same in an artificial line and actual open wire line if the length of the line, l, is 635 miles (1021 km.).

If the actual open line, however, is of No. 8 B. & S. gage, then with the same impressed e.m.f. the current at the end of 375 miles will be the same as at the end of the artificial line. The length of the open line equivalent to the artificial line can be conservatively placed at 375 miles. The oscillograph record shown in Fig. 7 gives the current distortion, due to the long line, which is found in this case.

Fig.5 shows the receiver of the author's printing telegraph system and Fig. 6 is another view of it with the head lifted from the tape to display the printing elements. It uses two local circuits; one energizes the magnetic circuit which normally holds the printing members off of the recording surface and polarizes them. The other is in series with a resistance and has its positive terminal connected to the receiver elements, which are here also the printing members, while the negative terminal is connected to the slightly moistened tape. A ferrocyanide of potassium solution, and iron tips to the receiver elements, have been found to be cheap and satisfactory. The line circuits are connected to the receiving spools and temporarily change the magnetic flux as

7. NOTE—See page 84, Fleming, *loc. cit.*

FIG. 2 [KINSLEY]

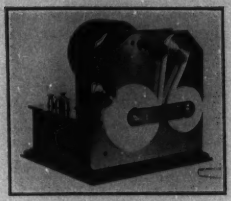

FIG. 3 [KINSLEY]

FIG. 4 [KINSLEY]

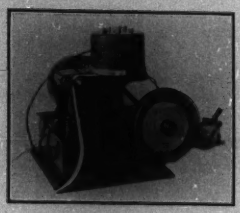

FIG. 5 [KINSLEY]

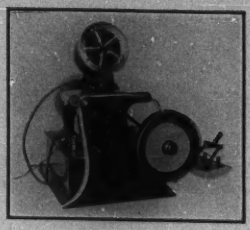

FIG. 6 [KINSLEY]

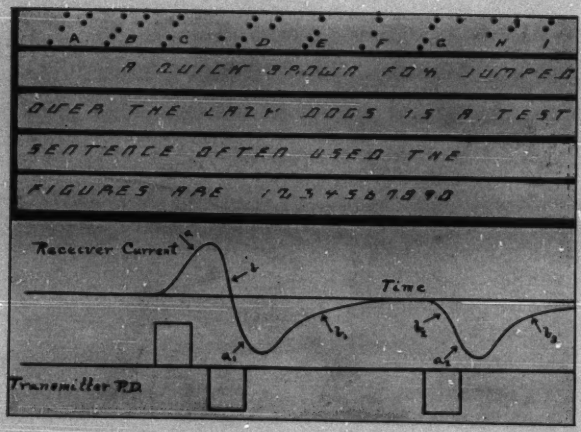

FIG. 7 [KINSLEY]

the signaling currents are received. It is found to be desirable to use various magnetic fluxes in the different circuits but in every case the magnetic density is not large when the parts of the magnetic circuit are proportioned as in this receiver.

The five elements are mounted on a circular frame so that the printing faces nestle closely together and form the pattern already shown in Fig. 1. This pattern is only one of several which have been tested. The form of the alphabet produced by it seems to be entirely satisfactory. A sixth element could be added if greater perfection were desired, while an alphabet of four elements which was thoroughly tried out was found to be legible to most people, but vastly inferior in appearance and doubtful of acceptance by the public. A sample of the transmitting tape and of the message as received is shown in Fig. 7, although the dark blue record on a slightly tinted background is a difficult object to reproduce photographically, and it is impossible to do justice to the original. The reproduction serves, however, to show the forms of all of the letters and figures as received over the whole of the artificial line, whose constants have been given, at a rate of 650 words per minute.

Operation of the Receiver Elements

The receiver is astonishingly consistent in its operation and it would probably be of interest to consider its functioning more in detail. The adjustment of the position of the core of a receiving magnet is accurately made by means of a reducing gear, all lost motion being avoided by the use of a stiff spring. After adjustment the receiver can be operated for a long time without any further attention. In one case, over four months elapsed without touching an adjustment screw, during which time it gave perfect service, then a break in the circuit made a repair and readjustment necessary. When a signaling current is received it will further magnetize the receiving magnet of one section of the receiver and reduce the magnetization of the one connected in series with it. The magnetization due to the local current lifts the receiver element from the paper and holds it against the core of the receiver magnet. When the signaling current slightly reduces the pull on the receiver element it is released, and the spring causes it to strike the paper, leaving its record, and then to rebound, when it is again caught by the local magnetic curcuit and held, ready for another release by the signaling current. The local current therefore does the work of distorting the spring

and the signaling current merely supplies enough energy to release it and to allow the stored-up energy in the spring to become effective. The receiving element has a flat spring rigidly attached to the core of the magnet which is energized by the local current. The natural period of the printing element can be made whatever is desired by varying the thickness or width of the spring and the size or location of the attached armature. The natural period of the receiving element should lie between rather sharply defined limits. Its period should be sufficiently long so that the signaling current has passed and the magnetizing current is again the controlling quantity before it returns to its resting position; and the period should be short enough so that the receiving element is back at rest before another signaling current intended to operate it is received.

Let us assume that the transmitter connects batteries directly between a line and the ground either with or without the condensers which are of service only when the source has large self-induction. Fig. 7 shows the current at the end of a 375-mile artificial line, due to the impressed constant e.m.f., as obtained by photographing oscillograph curves at both transmitter and receiver. The current is such as would be used in the vertical lines of a *G*. If we consider the negative current, which releases the element making the lower half of the vertical line for its two strokes, it can be seen that the natural period of the element should lie between definite limits. Since the element is more strongly held in place while the positive current impulse is on the line but is released when the negative current reaches a_1 and held again when the current is not more than b_1, then the period of the printing element should be longer than the time between a_1 and b_1 but shorter than the time between a_1 and b_2. There is one exception that is of minor importance, since it is desirable to avoid synchronism in general, that is, if the natural period is exactly as long as the interval from a_1 to a_2 then the second release will come at the proper time. If the natural period has a value such that the element returns to its initial position at any time between b_2 and b_3, except at a_2, then the resulting stroke will be given at the wrong time. This may not be so far wrong as to lead to illegibility, but will obviously give an imperfect result. The natural period used with this instrument as now adjusted lies half way between a_1 and a_2. This high natural period allows the use of the " " marks which are not considered a necessary part of the telegraph alphabet.

Hundreds of oscillograph records have been made, and it can be stated positively that with the present circuit and apparatus design no combination of currents can occur which will cause errors in the record. It is evident that a sufficient increase of speed or an increase in the length of the line without an appropriate reduction of speed will produce an inoperative condition, but as previously stated, the speed attainable is limited by the line and not by the terminal instruments.

The elements most frequently used are the two which combined make a straight upright line. This is produced, as already shown in Fig. 7, by connecting the battery to the line for 1/720 of a second and then reversing it for the same interval. This can be considered as a part of a periodic wave having the equation[8]

$$V_s = \frac{4E}{\pi} \sum_{0}^{\infty} \frac{1}{2m+1} \sin \frac{2m+1}{T} 2\pi t \qquad (4)$$

V_s = potential difference at transmitter at the time t counted from the time the positive potential is connected to the line.

E = potential difference of battery.

If we assume that the actual transmission will be equivalent to the sum of the series as far as the terms are appreciable, using $m = 0, 1, 2, 3$, etc., it will be possible to combine the arriving waves and obtain the arrival curve from the equation computed separately for each period, *i.e.*, for each value of m.

$$I_r = \frac{V_s}{(Z_s + Z_r)\cosh Pl + \left(\frac{Z_s Z_r}{Z_0} + Z_0\right)\sinh Pl} \qquad (5)$$

Z_s, Z_r and Z_0 are the impedances of the sending and receiving apparatus and the initial sending end impedance.

$$Pl = \alpha l + j\beta l = l\sqrt{r + jx}\sqrt{g + jb}$$
$$= 2.62 \angle 44^\circ 26' \text{ for } m = 0 \qquad (6)$$

8. The form employed is that used by Malcolm, *Electrician*, April 15, 1912, p. 916; eq. 32.

$$Z_0 = \frac{\sqrt{r + jx}}{\sqrt{g + jb}} = 285.5 \angle 45^\circ \text{ for } m = 0 \tag{7}$$

$Z_s = 0$ when batteries are used.

$$Z_r = 56 + j\,859 = 862 \angle 86^\circ\, 15' \text{ for } m = 0 \tag{8}$$

$$\text{For the first harmonic, } m = 0,\ I_r = \frac{V_s}{2320 \angle 174^\circ\, 7'} \tag{9}$$

The 2d harmonic, $m = 1$, has an amplitude of only $2\,\frac{6}{10}$ per cent of the first, and 3d harmonic, $m = 2$, has an amplitude of only $\frac{35}{100}$ per cent of the first.

In other cases with shorter lines the harmonics up to the fifth may be appreciable, but they in no way interfere with the operation of the receiver if the receiving elements are properly designed.

At the receiver, the current flow, so far as it materially affects the printing elements, is therefore a sine wave of frequency 360 periods per sec., as is apparent from an inspection of the oscillograph curves of Fig. 7.

No estimate will be made of the cost per message, but the various items which have rendered other printing telegraphs too cumbersome or expensive for general commercial use are here conspicuously absent. The whole receiving and printing part of the mechanism can be easily held in the hand or carried in one's pocket. Aside from the paper drive and the power circuits there are only five moving parts and they consist of stiff flat springs rigidly attached to the frame. The movement of each is less than 1/25 of an inch (one mm.) and there is no possibility of their getting out of order or needing adjustment. If the paper drive is started by a line impulse from the transmitter, a message could be received without the necessity of an attendant ever being present. The receiver, due to its extreme simplicity and entire absence of delicate parts, would have its first cost considerably less than that of a single sensitive relay. The cost of maintenance and operation will obviously be reduced to a minimum, since on account of its simplicity and speed the number of attendants and their individual skill will be far less than at present needed. Of the

entire system, the most complex part as well as the most expensive is the commercial typewriter. It is not altered in any way, and if large users of the telegraph should themselves prepare the transmitting rolls the typewriters would be available at other times for general office purposes.

The widespread interest in and need for a cheaper telegraph service should undoubtedly lead to the adoption of some machine method of telegraphy which would make possible a large reduction in telegraph tolls.

DISCUSSION ON "A HIGH-SPEED PRINTING TELEGRAPH SYSTEM" (KINSLEY), DETROIT, MICH., JUNE 26, 1914.

C. R. Underhill: Mr. Kinsley is certainly to be congratulated on the very ingenious device which he has brought out, and I must say that it is one of the most surprising forms of high-speed printing telegraph instruments which have come to my notice. It seems, however, that it is necessary to use two wires and ground, which makes the line expensive, particularly since the machine is designed, I presume, for long-distance transmission, as that would be the service in which it would apparently have its greatest value, but the use of two wires may not be so detrimental as at first appears. Probably one great reason why the printing telegraph has not been adopted more in this country as compared with European countries is because in foreign countries the telegraph is used for letter-writing. Abroad, I understand that it is customary to send a telegram instead of a letter, and for that reason the traffic is increased and the price is brought down.

Some years ago, in 1904, I brought out a printing telegraph which has never been made public except through the patent offices of the world, and which has been kept quiescent for certain reasons which need not be mentioned. My object in bringing out this telegraph instrument was based on the fact that the Morse system is in universal use not only in this country, but abroad, not only for short distances, but for great distances, both for wire and wireless telegraphy, and might be called the universal telegraph system. This instrument to which I refer was so designed that it would print in English characters on a tape, something like a stock "ticker", that is, it would translate from the dots and dashes of the Morse code into type. I had a great deal of difficulty on account of certain letters in the Morse code, *i. e.*, C, O, R, Y, Z. I had no difficulty in making it work on the Continental or Universal code.

There is a point I wish to bring up in connection with the introduction of a machine of this character. The telegraph companies of the United States and Canada are very slow in adopting the Continental or Universal code, although it is used abroad, and in the wireless field. It is not unusual for operators to receive messages in the Continental code and send them out again in the Morse code. On the long trans-continental lines they do use the Continental code, to a certain extent. It has been shown that operators in the wireless field readily learn the Continental code, although accustomed to the Morse code, yet the telegraph companies will not adopt it. There seems to be some inertia there.

I would like to ask what effect the line leakages due to weather have on this instrument. Although Mr. Kinsley stated there is no local battery, I understand a local battery has to be used for holding up the armature, as he explained. I would like to

know whether a careful balance has to be maintained in the magnets. We know the quadruplex will not work well whenever there is considerable leakage on the line on account of the weather. I would like to know how line leakage affects these magnets, and whether adjustments have to be made, locally, when the line current varies.

My experience with the telegraph instrument I mentioned has, I think, an important bearing on the introduction of a machine of this kind. I took it before the high officials of one of the large telegraph companies. They received it very nicely and said it was a very ingenious device, etc., but they led me into the operating room and showed me a man sitting before a resonator, with a sounder in it, the man operating a typewriter and taking the matter down at the rate of about thirty-five words a minute. The official said, "You watch that operator." By chance the operator "broke," took the paper out of the typewriter, made a correction on it, put it back and started typewriting again at the rate of about one hundred words a minute. During this interval he was storing the message in his head. The official said, "You bring us a machine that will dispense with the operator, and we will put it in."

In connection with the matter of the two wires, I wish to add that one of the officials, in speaking of the capacity in connection with any machine, said, "Whenever further capacity is needed, we have plenty of wires running between New York and Chicago, and all we have to do is to tap in on another wire." It may be in a case like that, since they have so many wires, it makes no difference whether you use a single wire or three wires at a time. Incidentally, I might add that a code system like the Morse or Continental is applicable both to wire and wireless, whereas I know of no other system which can be applied to both. I have made my system work on the wireless.

Ralph W. Pope: I was particularly struck with the novelty and ingenuity of the system proposed by Mr. Kinsley. It takes me back to the time when there were objections raised to the printing systems then in use. I first learned to operate the Hughes printing telegraph in 1858, and learned the Morse as a side issue and for amusement. What was amusement then became business thereafter, for the printing instruments were gradually discarded. In the days of the printers, the first being the House, followed by the Hughes, we were very careful about sending out good copy, that was perfectly legible and could be read without difficulty by any one. The House machine was inferior in this respect, for the reason that instead of printing direct from the type it made an impression through a carbon tape onto the paper, and the fine lines of the letters were somewhat blurred and the copy looked smutty, but still it was very good if the tape was kept in good order. The Hughes printer, which followed, printed directly from steel engraved letters, the same as the ordinary type used in printing a news-

paper, while the House was similar to the carbon tape on the typewriter. You see we have made considerable improvements, in that the result of a carbon tape today is better than that we used to get from the House printing tape years ago. Legibility, then, was one of the desirable things, but there was another important feature, important in a negative sense—business men did not like the tape, for the reason that it was not the proper kind of a document to file away, and when I was a private secretary and received these tape telegrams in the course of business, one of the jobs of the office boy was to tear the tape into pieces five or six inches long and paste them on a sheet, so that we could file them away. In those days, as I recall, no effort was made towards producing the "page printer," but today we have page printers. The type wheel shifts along on the shaft, and when it comes to the end of a line it goes back. I am not familiar enough with the experiments of Mr. Kinsley to know whether he has undertaken anything of that kind.

We come then, to this question of legibility, and I notice in the paper the author says that the letters and figures can be made more perfect by the use of a sixth element. In the samples presented by Mr. Kinsley it does not seem to me that the figures, more especially, are sufficiently distinct. Figures in a telegram are quite important; I do not refer so much to figures in the body of the message, making errors in reading quotations, for instance, but in the addresses on messages; and the number on the street is not so important as the number of the street itself. Because, if you have a telegram addressed to the right street you are quite likely to find the right number. I have noticed the figures 168, as they appear on this slip. In Washington, that might be read, possibly, 16 B street, or in New York it might be read, instead of 168th street, 108th street, not by an expert, but by the boy who addresses the envelope. So that it appears to me that the figures should be so perfect that there is no possibility of there being errors made in reading them. That is, as you will see, more important than the matter of letters.

For more than forty years, experimenting has been going on with systems of rapid telegraphy. That has always meant the preparation of the message in advance by perforating paper, and running it through rapidly, in order to get this high speed of 650 words a minute. That means that the sending matter must be divided up amongst a few "punchers," as they are called, whereas with the Kinsley instrument, when the message is ready for delivery, it has gone through no other process at the receiving end, and the tape is supposed to be ready to deliver. That has not been the case heretofore with these received messages, they had to be divided up and recopied, on the same principle that they were divided up for punching. While it is desirable, perhaps, to get this high rate of speed, there is another question to be considered, which was brought to my attention

by Sir William Preece at our meeting in April, 1907, when we discussed the Rowland printing telegraph. Sir William said that one of the difficulties they had with these fast systems in England was to get business enough to work the system up to its capacity. There were only a few through trunk lines between London and Liverpool, and London and Glasgow, perhaps, where they could work these fast systems economically, for the reason they would run out of business and would have to wait for more.

I consider that telegraphy, when you recognize its value, is one of the cheapest things we have, but the average individual rarely sends a telegram on his private account. It is only the great business houses, especially brokerage houses in the large cities, which spend such large amounts in telegraphing. I have gone sometimes from one year's end to the other without sending a private telegram, but that is more especially the case since we have had the telephone. So that the cost of telegraphing is a very small item in the expenses of the average consumer.

Years ago I wrote an editorial on this subject, and took for my text the cost per ton of making stoves in Troy. I happened to run across this list of items that went to make up the cost of a ton of stoves—so much for iron, so much for labor, and so on, running up, as I recall it, to about $80 a ton, while for postage and telegraphing, which were lumped together, it was $1 in the cost of a ton of stoves, and bad debts were placed at $2, so that really this amount of bad debts was double the cost of telegrams and letters.

I have always maintained that telegraphing should not be cheapened. This also was an argument put forward by Mr. Swain, who was one of the officers of the first telegraph company in the country, I think, at Philadelphia, when he said they were making a mistake in trying to cheapen the work of the telegraph.

Before typewriters were used it was considered necessary that every operator should write a clear hand, not necessarily handsome, but plain. It is now obligatory, in most offices, to use a typewriter for transcribing messages instead of longhand. So, we have seen an evolution, even in the simple Morse, first from the use of a metal type notched, for transmitting purposes, set up in a stick and run along, because the inventor thought the operator could not make the signals plainly enough. Then we went to the key sending and received messages on the tape. Then the embossing register was discarded, when the operators discovered they could read the signals by sound and do it much more quickly, and more accurately, and keep up with the sender. That is one thing you lose in any system of the kind under discussion, you lose that time which is required in punching the tape. In receiving by sound, ordinarily the operator is close up with the sounder; to be sure, as the previous speaker has said, they may lag behind for a dozen words, and catch up later—that is one of the peculiar features of Morse telegraph-

ing, the ability of the operators to carry along, some of them twelve or twenty-five words, perhaps, behind the sounder and keep these words in memory, while they are turning their carbon sheets, or putting in fresh carbon sheets, and the various other details which are necessary. That is what I used to do when I had to wait on myself and was fixing up carbon sheets for three copies. While I was doing that, the sounder was going on, and when I began the next page I would be a dozen words behind and then would catch up, and be ready to change the next page.

I was speaking of the evolution of the Morse simply by the practical experience and growing skill of the operators. I might say there was always a rivalry between the sending operator and the receiving operator, as to which could work the faster, whether the sending operator could send faster than the receiving operator could receive it, and it was about neck and neck until the typewriter operator arrived. When the typewriter came, the receiving operator had it all his own way, he could almost take a nap in between times, because he could take ten or fifteen words more per minute more than the sending operator could send.

What has happened now? The telegraph company has eliminated all of the conventional signals, formerly required in sending messages. They used to put "ahr" for "another," and "fm" for "from" on our messages. Now, the company, to save time, has eliminated these things, and the receiving operator must be still more expert, because he has no breathing spell. As the operators found they could receive much faster with the typewriter, the company said, "If you can receive so much better by typewriter, you must all do it." So they all do it. The typewriter is in practically universal use today.

We have seen that the receiving operator has more leeway with the use of the typewriter, but in press reports the Phillips code is used by the sender. The Phillips code is an authorized system of abbreviation. This does not apply to the ordinary messages, which are not allowed to be abbreviated. I will give this instance of one word—"scotus." This means the Supreme Court of the United States. When a man receives the word "scotus" over the wire, on his typewriter he must write out the words "the Supreme Court of the United States." That is rather an extreme instance, but it is an example—"scotus" is made up of the initials of the words. The code is copyrighted by Walter P. Phillips, the inventor, and is published in book form.

A word about the present Morse alphabet. It is a very simple matter for an operator to send or receive by either code if he is familiar with them, just as it is easy for Mr. Mailloux, for instance, to state a proposition in nine different languages, so that it is simply a question first, of the Morse operator learning the Continental code, as it is called, which is a very simple matter. It is now required in the wireless service. It would

probably only be necessary for the telegraph companies to say that after a certain date, the first of October, for instance, the Universal alphabet shall be used instead of the Morse. But the question of superiority is not quite settled. When the old Bain chemical telegraph, which was a rival of the Morse, was in operation, the Bain alphabet was used, which by many was considered superior to the Morse, and there were many operators, especially in New England, who knew both alphabets. The Bain code is now obsolete.

There is one more question I want to ask of the author. Fig. 7 shows that the dots used for "C" and the dots used for "G" are practically the same, in the case of "G" there being one added, and the same combination of double dots appears in the case of "D." I was a little at a loss to know how the combination came in "I," because the curve is reversed, and I am not certain whether it is possible to reverse the curve or not.

George S. Macomber: I think we should congratulate Mr. Kinsley on his very happy and novel combination of inventions. It seems to me that almost all inventions of this kind are really new combinations of things known before. In the present case we have a type printer operated by electromagnets, combined with an electrochemical telegraph recorder.

All high-speed telegraph recorders may be divided into two general classes, electromagnetic and electrochemical. We have three sub-classes of electromagnetic recorders: (a) those operated by non-timed step-by-step mechanism, as in the case of the various "tickers"; (b) those operated by synchronous motors, as in the case of the Hughes, the Phelps, the Baudot, and the Rowland printers, and (c) those operated by non-synchronous timed impulses, as in the case of the Morkrum printer, in which six electromagnets are successively and automatically operated at definite time intervals after the first or starting impulse is received, and in which the various letter combinations are determined by the arrival or absence of positive or negative current impulses at the receiver as each of the timed magnets respectively operates. We have two sub-classes of electrochemical telegraph recorders: (a) those using unidirectional current, as in the early Bain two-wire telegraph; and (b) those using both positive and negative line current impulses, as in the Foote and Randall and the Delany telegraphs.

Mr. Kinsley's telegraph uses a perforated tape with five rows of perforations somewhat like that of the Pollak-Virag telegraph tape; a transmitter which sends both positive and negative current impulses over the line as did that of Foote and Randall; a two-wire transmission line as did the first Bain system; and a chemically prepared tape, similar to that used by Bain and Delany, in a recorder so arranged as to make, electrochemically, successive lines so placed on the tape as to form or at least imitate type print.

I want to ask Mr. Kinsley how many unit time intervals are required, on the average, by his recorder, per letter. It appears

from Fig. 7 that some letters, as, for example, "B," must require more time than other letters, such as "I".

I wish also to record a correction of the generally accepted notion that Alexander Bain was the first to produce a chemical telegraph recorder, for as early as 1828, Harrison W. Dyer built an electrochemical telegraph recorder and operated it over a line several miles long.

Carl Kinsley: In answering the first question, in regard to leakage and difficulty of balancing, since there is no battery at the receiving end which takes part in the operation of the line current, the battery at the receiving end merely magnetizes the local circuit. In the sending end, is the only battery which takes part in the operation of the line. In instruments with a neutral relay, such as the Edison quadruplex, half a dozen different operations have to be gone through with in order to receive one signal, to quote from "American Telegraphy," by William Maver, Jr., (New York, 1903; page 198):—"it is quite demonstrable that during the making of a dash on the neutral relay at one station the distant pole-changer may reverse its battery several times; the home pole-changer may do likewise and the home transmitter may increase and decrease the electromotive force of the home battery, repeatedly. At the same time, and, of course, as a result of the foregoing actions, the home neutral relay may have had its magnetism reversed several times, and the signal will have been made, partly by the home battery, partly by the distant and home batteries combined: partly with current on the main line, partly without: partly by the main line 'static' current, and partly by the condenser current, and yet on a well-adjusted circuit it will have been heard on the quadruplex sounder as clearly as any dash on an ordinary 'city line' sounder."

There is nothing of that kind in connection with this instrument. There is merely a positive and negative to line from the transmitter, and it works one particular element, or in one case two elements, and tends to hold up the other one on the line, because these elements are in series with each other; consequently there is no difficulty—any line that is good enough to operate a polarized relay will operate this with current less than is necessary with the usual polarized relay, because the operating energy does not go over the line; the operating energy is supplied largely by the local circuit, and what goes over the line is merely enough to upset the balance between the local magnetic circuit and the tension on the spring.

C. R. Underhill: In case of leakage, could you get enough current to operate satisfactorily?

Carl Kinsley: You can get all that you can from any telegraph line for operating any relay. There is a point where all telegraph lines break down.

C. R. Underhill: Does that come from that kind of balance—in case you had plenty of current, or very little current, would it have to be adjusted to balance?

Carl Kinsley: There is no balancing on the line in that sense. You merely have to arrange the instrument so that it will always operate when the current reaches a minimum value, and it will operate for any value above that. There is no margin of working in that sense.

In regard to the use of six elements, I like the five better, as being more simple to operate. The sixth element will give, possibly, some increase in the beauty of the alphabet, because there can be made certain distinctions with six which cannot be made with five, but, in my opinion, the alphabet made with five elements is perfectly legible. However, if for any reason the five-element method is not sufficiently graceful, then it is possible to use the sixth. As a matter of fact, four elements have been used, and give a legible alphabet to readers familiar with its use but it lacks the characteristic of being familiar to all.

In regard to Fig. 7, it was suggested that "C" differs from "G" in that there is a second use of the lower half of the vertical line in "G". How that differs from "O" is that there is no second use of the upper half of the vertical line. In the "G" the currents are first positive and then negative over one line, second positive and then negative over the other line, the negative following immediately after positive, and then a wait, and then another negative over the second line. Sometimes there are two impulses in the same direction following each other, but they are followed in the next vertical line by positive and negative. There is no building up of charge in the line, and it has been found that the line can handle two, where it cannot handle five successive impulses in the same direction. This system keeps the line clear for each succeeding letter, starting as it does with positive and negative, which has the effect of clearing the line.

There was another question, I think by the following speaker, asking how many impulses were taken per letter—he said how many "time impulses;" I think he meant how many impulses per letter. That varies with the letter. The time element enters into this system—a certain time must be allowed for the receiving tape to get away before printing the succeeding letter. It does not make any difference how many impulses are sent in making a certain letter. The time allowed for a single letter is sufficient for twelve time impulses. As a matter of fact the number of current impulses in that time may only be three or four, but sufficient time must be allowed for the paper to clear. It does not increase the speed to have fewer current impulses, since it is necessary to allow a certain time interval to elapse to give room for the next letter. Twelve time intervals will give sufficient space, and inside of that time there can be as many current impulses as you please, since the positive and negative follow each other and keep the line clear.

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TOLL TELEPHONE TRAFFIC

An Experimental Study of the Relationship between Circuit Loads and Delay to Traffic

BY FRANK F. POWLE

ABSTRACT OF PAPER

Experiments are described to determine the relationship between telephone circuit loads and the corresponding delay to traffic. The operating methods employed and the number of circuits available determine in general the number of messages per day which can be handled over a single toll circuit. The average delay to traffic obviously depends upon the number of messages per circuit per day, or the circuit loads. With a given load factor, increase in the circuit loads will increase the average delay to traffic. At the same time the revenue per circuit mile will correspondingly increase. The practical limit, however, is approached when the delays to traffic reach a point where the service is unsatisfactory. The results of the experiments described illustrate the fact that increasing circuit loads increase the delay to traffic, and vice versa. The revenue per circuit mile is directly proportional to the product of the circuit load and the toll rate per minute-mile; consequently the relationship between the quality of service and the toll rate is generally obvious, assuming a certain rate of return on the plant investment.

THE NUMBER of telephone messages per day which can be handled over a single toll circuit, as is well known, depends upon several considerations. Chief among these are the operating method employed and the number of circuits required to handle the total traffic between the given terminals. A complete dissertation upon toll operating methods would extend far beyond the scope of the present paper, and only the simplest or fundamental methods will be mentioned. The earliest method, and one still used to a great extent in handling small volumes of traffic, is the direct ring-down, in-and-out ticket (or two-ticket) method. In this method the operators signal each other direct, over the talking or message circuit, by ringing in the usual manner; the outward operator makes a complete ticket, and times and supervises the connection; the inward operator also makes a duplicate ticket, but does not time the connection. This method has been materially improved by

eliminating the inward ticket, and by having the outward operator deal directly with the called party at the destination instead of through the intermediary of an inward operator who repeats the details back to the outward operator. In some cases the last method has been modified to the extent of having the inward operator make a memorandum ticket or so-called skeleton ticket, for checking purposes, but this is usually eliminated if possible. Other operating methods, special in their nature, apply when the volume of traffic is very large, but do not come within the scope of the present discussion.

It is not necessary to dwell at length upon the fact that the number of messages per day, per circuit, increases (other factors being the same) as the volume of traffic and the number of circuits operated in one group to handle it also increase. That is, the circuit efficiency increases as the number of circuits or trunks in a group increases, and more messages per circuit, per day, can be handled in a large group than a small one, with the same average delay to traffic and equal load factors.

The effects of the operating method and the size of the trunk group upon the circuit loads (messages per circuit per day) are usually discussed from the standpoint of a certain fixed quality of service, that is, a certain average delay to traffic which is maintained as a standard. This period of delay is generally accepted as the interval from the time the calling subscriber gives his call to the recording operator, until the line operator establishes the connection or returns a definite report in regard to the called party. It seems fairly obvious, however, that there must be some definite relation between the circuit loads and the average delay to traffic. In other words, with a constant load factor, the effect of increasing the circuit loads will be to increase the average delay to traffic; at the same time the toll revenue per circuit-mile will correspondingly increase. Naturally a limit will be approached when the traffic is delayed to such an extent that subscribers complain of the delay and a loss of business is threatened.

This relationship between circuit loads (traffic density per circuit) and average delay to traffic, if not already clear, can be illustrated by a simple analogy with railway transportation. Given a fixed volume of traffic (passenger or freight) to be transported, the delays in traffic movement will be least when the train service is as frequent as it is possible to arrange it; but unless the volume of traffic is very large, the train loads may

not be large enough to produce an adequate net revenue per train-mile. In order to increase the train loads to a point where the operating revenue per train-mile will exceed the cost by a reasonably profitable margin, it will perhaps be necessary to resort to less frequent train service. This implies a longer average interval between trains, and consequently a longer average period of waiting or delay before the traffic is moved. The parallels in the analogy are between the number of trains and the number of toll circuits, between train loads and circuit loads, and between delays to railway traffic and to toll traffic, a fixed volume of traffic in each case being assumed.

The general problem is therefore one of the highest commercial importance, since it is perfectly obvious that under a given schedule of toll rates there is a certain standard of service which cannot be exceeded without the sacrifice of profits, and

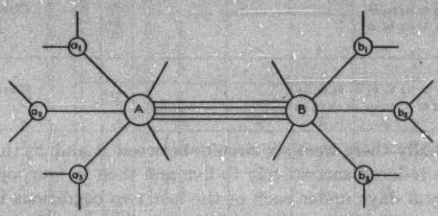

FIG. 1—PORTION OF A TOLL SYSTEM—TOLL CENTERS AT A AND B

the faster the service as a whole the higher must be the rates for the same percentage of profit. It is not at all the intent in this paper to reach any conclusions as to the commercial side of the question, but simply to present certain experimental data bearing on the general principle.

LAYOUT OF EXPERIMENTAL CIRCUITS

The general layout of the toll lines used in the experiments here described is shown in Fig. 1. The group of circuits upon which the experiments were made extended between A and B, the latter representing two toll offices, or toll centers. The greater portion of the traffic either originated at A and terminated at B or vice versa. The remainder of the traffic was of a through (instead of terminal) character, necessitating the use of tandem circuits. For example, a call originating at A and destined for b_2 or some point beyond, would have to be switched at B; in some cases the call would be passed to the operator at B, who

would take the details and record them on a through ticket, and then pass the call to b_3, while in other cases the operator at B would connect the line through to b_3 and the operator at A would pass the call to the operator at b_3. The entire traffic passing over the group of circuits between A and B can be classified as follows, for convenience.

TABLE I

CLASSIFICATION OF TRAFFIC OVER GROUP OF CIRCUITS BETWEEN A AND B IN FIG. 1.

A to B B to A	Class 1
A to b_1 or b_2 or b_3 B to a_1 or a_2 or a_3	Class 2
a_1 or a_2 or a_3 to B b_1 or b_2 or b_3 to A	Class 3
a_1 or a_2 or a_3 to b_1 or b_2 or b_3 b_1 or b_2 or b_3 to a_1 or a_2 or a_3	Class 4

Normally there were six circuits between A and B; this number was reduced successively to five and then to four, operating for several days under each of the last two conditions in order to secure reliable test data. A study of the traffic was then made from the tickets, excluding any days such as Sunday or Saturday when the traffic is not normal, and also excluding any days when there was any wire trouble on any of the circuits in the group. Of course it should be understood that the through traffic did not necessarily originate or terminate at the first office beyond A or B, but in some cases involved offices reached by two or more switches.

SUMMARIES OF TEST DATA

The operating method employed in handling the terminal business (class 1 traffic) between A and B (Fig. 1) was the direct ring-down, single-ticket method, while all other traffic was handled by the double-ticket method. The through business was handled in some instances by means of relays, or through tickets at the switching point, and in other cases by straight switches (no ticket).

The summary of results is presented in Table II. Recapitulating, the class 1 traffic is the terminal business between A

TABLE II

SUMMARY OF AVERAGE DAILY TRAFFIC OVER THE GROUP OF TOLL CIRCUITS BETWEEN *A* AND *B* (FIG. 1.)

Number of circuits in use	Class 1 traffic		Class 2 traffic		Class 3 traffic			Class 4 traffic			Total number of messages (2 switches taken as 1 message)	Number of messages per circuit	Revenue per circuit mile	Number of days' business averaged
					Relayed		Switched	Relayed		Switched				
	Number of messages	Average delay (min.)	Number of messages	Average delay (min.)	Number of messages	Average delay (min.)	Number of switches	Number of messages	Average delay (min.)	Number of switches				
6	124	7.0	19	17.	4	9.2	25	3	14.	2.	164	27.3	$.187	3
5	144	12.2	22	25.	8	5.8	41	3	20.	2.	198	39.6	.255	3
4	140	21.1	17	30	13	21.	43	2	6.	1.	193	48.2	.314	2

and B (Fig. 1), the class 2 traffic is the through business originating at A and B, the class 3 traffic is the through business terminating at A and B, and the class 4 traffic is the through business to and from points beyond A and B but passing over the circuits between the latter. There was no simple way of determining whether each through switch at A and B was set up for the transmission of a message, but in general the number of switches exceeds the corresponding number of messages and it was arbitrarily assumed that there was one message for every two switches. The average duration of a message was approximately four minutes. The rate schedule in force was the same throughout each 24-hour period.

Table III shows a summary of lost and delayed business,

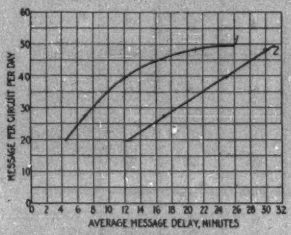

FIG. 2—CURVES SHOWING THE RELATIONSHIP BETWEEN CIRCUIT LOADS AND AVERAGE DELAY TO TRAFFIC
Curve (1) for terminal business.
Curve (2) for originating through business.

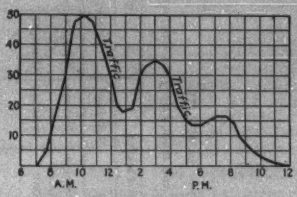

FIG. 3—TYPICAL LOAD CURVE OF TOLL TRAFFIC

for the same periods as represented in Table II. In all cases the traffic figures represent one day's business, being an average of several day's business, as indicated in the last column in Table II.

DISCUSSION OF RESULTS

The relationship between the average delay to terminal business (class 1 traffic) and the circuit loads is plotted in curve (1), Fig. 2; the similar relationship for the originating through business (class 2 traffic) is plotted in curve (2), Fig. 2. The underlying data are taken from Table II. These curves bring out forcibly the general conclusion of the paper, namely, that increasing circuit loads are accompanied by increased average delay to traffic. For example, taking the terminal (class 1) traffic, five-minute service corresponds to a circuit load of 21

messages per circuit per day, in a group of about 8 circuits; six-minute service corresponds to a circuit load of 24 messages per circuit per day, in a group of about 7 circuits; seven-minute service corresponds to a load of about 27 messages, eight-minute service to 30 messages, ten-minute service to 35 messages, etc. The following Table IV was prepared in this manner from curve (1), Fig. 2; this of course is based primarily on handling a substantially constant volume of traffic.

TABLE III

SUMMARY OF LOST AND DELAYED BUSINESS.

Number of circuits in use	Per cent of originating calls (A and B) lost	Number of calls delayed by "no circuit" conditions	Average no-circuit delay, on delayed calls (min.)	Number of calls lost on account of "no circuit" conditions
6	18%	25	11.8	None
5	17%	62	12.9	1
4	21%	99	16.9	1

TABLE IV

CIRCUIT LOADS FOR VARIOUS GRADES OF SERVICE WITH CONSTANT VOLUME OF TRAFFIC AND A GROUP OF 4 TO 8 CIRCUITS

Average delay to terminal traffic (min).	Circuit loads in total messages per circuit per day
5	21
6	24
7	27
8	30
9	33
10	35
11	37
12	39
13	41
14	42
15	44

The volume of class 3 traffic, Table II, is so small that the data on average delay are unreliable. This is more obvious by reference to a typical load curve, Fig. 3. Evidently there is a large probability that these relatively few class 3 messages were handled during some other period than the peak, or the "busy hour;" and in such case the delay would be less, owing to lighter loads on the circuits. The same is true of class 4 traffic. The daily load factor was in the vicinity of 30 per cent.

The delay to originating through business (class 2 traffic), destined to scattered points to which the business did not justify

individual direct circuits, is shown in curve (2), Fig. 2. Of course this delay can be minimized by eliminating relay tickets at switching points and substituting straight switches.

The use of averages, particularly in reference to the delays to traffic, does not convey complete information as to the character of service, since some of the calls will inevitably be delayed longer than the average, and others less. In order to bring out fully the quality or speed of toll service it is desirable to resort to curves of the type shown in Fig. 4. These curves show the percentage of calls handled with a given delay, or less, and therefore reveal the extremes. The three curves there shown give in more detail the grade of service obtained during

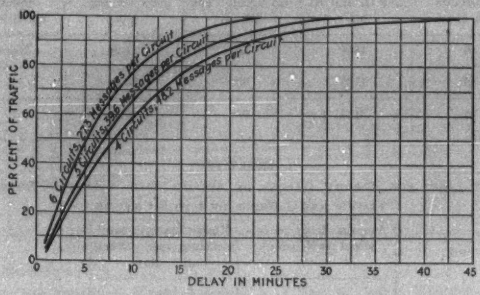

FIG. 4—PERCENTAGE OF TERMINAL TRAFFIC HANDLED WITHIN A GIVEN INTERVAL OR LESS

the tests whose results are recorded in Table II. Each of these curves applies only to the terminal business, or class 1 traffic; the average delay in each case may be found in Table II.

The results given in the paper, although they apply specifically to conditions which do not differ widely from those described, nevertheless serve to illustrate the fundamental principle that increasing circuit loads increase the delay to service, and vice versa. The revenue per circuit-mile per day, or per annum, is directly proportional to the product of the circuit load and the toll rate per minute-mile. Consequently the relationship between the quality of service and the toll rate schedule is in general an obvious one, assuming of course that a certain fixed percentage of return on the plant investment is maintained in all cases.

DISCUSSION ON "TOLL TELEPHONE TRAFFIC" (FOWLE), DETROIT, MICH., JUNE 26, 1914.

J. Lloyd Wayne, 3rd: I think this subject of telephone toll traffic is very close to the heart of every operating telephone man and it is certainly to be appreciated if we can bring before the public the fact that speed costs money. The telephone message being largely intangible, the general public is apt to get the idea that it does not make any difference in your cost of operation whether you get the connection through quickly or slowly. The telephone user is liable to forget the simultaneous demands of the many other telephone users. This paper brings out evidence of the practical necessity of lining up the toll calls in the order of receipt, if rates and earnings on the plant investment are to be reasonable. Every toll telephone plant representing a large investment may be likened to a transmission plant subject to very high peak loads. A large part of the day the plant is not carrying anywhere near its capacity and at other parts of the day it may be subject to overload demands. Unfortunately these busy or overload periods occur at the hour when business is at its height and thus at the time when speed means the most to the patron.

Again, with our telephone toll plant the revenue is based on the productive time. Furthermore, with each short period of production we must necessarily have a nonproductive time during which the circuit must be built up from the calling party to his correspondent. It is as though we had a power transmission line, the revenue from which is derived from the number of minutes of useful production of a motor load at one end, it being necessary to stop and start both generator and motor, free of charge, before and after each useful run. It is very evident that the less this nonproductive time, especially at busy periods, the greater the number of messages that can be handled. Mention is made in the paper of the single-ticket and two-ticket methods. The former method cuts down the nonproductive time and gets the business over the line more quickly. However, with the two-ticket method there is a record of the message at two points and thus there is less liability of losing track of completed calls.

The paper calls attention to the fact that with a certain average speed of service, some of the calls will be handled considerably more slowly than the average. This is clearly shown by comparing the curves in Fig. 2 and Fig. 4. The middle curve of Fig. 4 represents approximately 40 messages per circuit. Now if you will observe curve 2, you will find that at this rate the average speed of service as shown by the abscissa is 12 minutes, while the maximum delay shown on the middle curve of Fig. 4 is some 30 minutes, or two and one-half times this. It is well recognized that speedy service is a good advertisement and re-

sults in the filing of many messages which would not otherwise be offered. In devising a telephone toll plant we must continually have in mind the proper balance between (1) the number of messages to be handled, that is, number of paid minutes per day, (2) the necessary speed of service, (3) practicable rates, and (4) the corresponding number of circuits required, that is, the plant investment.

Presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Spokane, Wash., September 9, 1914.

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THE EFFECT OF DELTA AND STAR CONNECTIONS UPON TRANSFORMER WAVE FORMS

LESLIE F. CURTIS

Abstract of Paper

The purpose of the paper is to show the distortions resulting from different symmetrical three-phase connections of generator and transformers without transmission line, as dependent upon the hysteresis cycle and the admittance of the transformers at no-load.

Tests were made with the oscillograph to show the no-load exciting current and voltage waves of three single-phase step-up transformers when the windings of the generator and both sides of the transformers were connected in all possible symmetrical delta and star relations.

Tests are divided into four groups, according to the connection of the generator. In all cases normal low-tension line voltage was held, but voltage and current measurements were considered less important than the recording of wave forms.

Oscillograms are given in each case and the relations between the flux, voltage, exciting current, and the hysteresis cycle are shown in two instances.

The author points out that the best voltage wave forms will, in general, be obtained with a star-connected generator and delta-star or star-delta connected transformers.

Introduction

It is well known that the method of connecting three-phase transformers, or single-phase transformers upon three-phase lines, influences the character of the potential and current waves, in that the type of connection limits the per cent of the harmonics of e.m.f. which may appear between lines and the per cent of the harmonics of current which may appear in any line. It is not the purpose of this paper to bring forth any new discoveries, but to present a series of wave forms, taken with the oscillograph, showing the wave distortions which are likely to occur in the different symmetrical three-phase connections.

Oscillograms of potential and exciting current were taken at no-load upon three single-phase, 10-kw., 1100-110-volt, 60-cycle step-up transformers when connected in all possible combinations of delta and star. The generator used was a 7.5-kw., 60-cycle machine, so arranged as to give the desired voltages

when connected either delta or star. It was thought that any distortions would be a maximum with the large transformers connected to the smaller generator at no-load.

Throughout all of the tests the line voltage was held at 110 when the transformers were connected in delta, and at $110\sqrt{3}$ when the transformers were connected in star.

Since the transformers were very nearly balanced, wave forms were not recorded upon all of the phases.

Tests with One Transformer

Before investigating the wave forms with the three-phase connections, an oscillogram of exciting current with

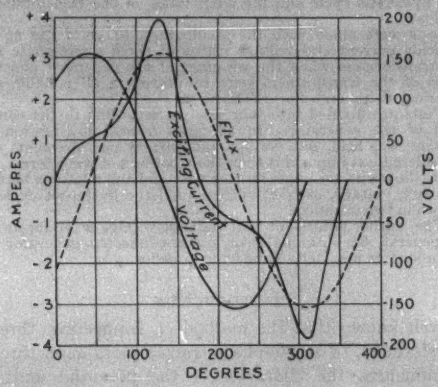


Fig. 2—Potential, Flux and Current Waves. Single-Phase Connection

a sine wave of e.m.f. was taken to determine the hysteresis cycle under normal conditions. This is shown in Fig. 1.

Fig. 2 shows the voltage, flux and exciting current, and Fig. 3 the resulting hysteresis cycle scaled from the original oscillogram.

Tests with Star-Connected Generator

The next set of tests was run with the generator connected in star. This gave practically a sine wave of e.m.f. between lines, except when the reactions in the transformers introduced a fifth harmonic.

With a star-star connection of transformers, the wave of exciting current is as in Fig. 4. Since no third harmonic can exist in the exciting current, one must appear in the transformer voltage, or the voltage to neutral, even though the line voltage remains a sine wave, because of the definite shape of the hysteresis cycle. This is shown in Fig. 5.

Fig. 6 shows the voltage, flux and exciting-current relations for the above connection. The hysteresis cycle is plotted in Fig. 3, showing the same general shape as for the sine wave of flux, but being smaller in area.

For the above test, normal line voltage (110 $\sqrt{3}$ volts) was

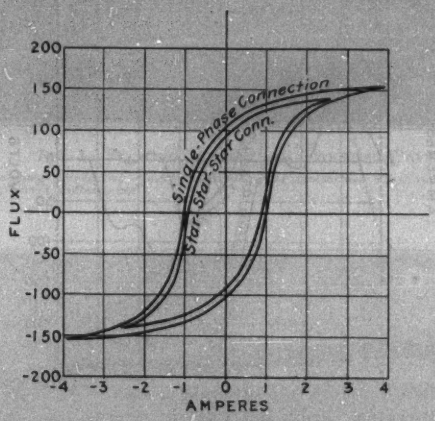


FIG. 3—HYSTERESIS CYCLES

held, but owing to the change in wave shape, the voltage to neutral was 121.0.

With one side of the transformers connected in delta, the third harmonic, which is lacking in the exciting current with the star-star connection, may flow in the closed delta. It appears only in the local transformer circuit. Fig. 7 shows the line current and the transformer current for a delta-star connection of windings. The admittance of the transformers is such that a fifth harmonic in excess of the amount demanded by the hysteresis cycle appears in the line and transformer currents. This causes a fifth harmonic to appear in the e.m.f.

waves, as is shown in Fig. 8. Curve 2 shows the characteristic flat-topped delta voltage, or high-tension voltage to neutral, for this connection. Curve 1 shows the high-tension line voltage, which is peaked because of the vector difference of waves containing the fifth harmonic similar to that shown in Curve 2, 120 deg. apart.

It will be noted that the reaction causing this distortion originates in the transformers, since the wave of exciting current

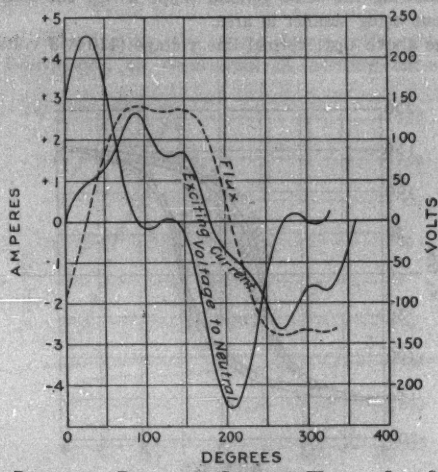
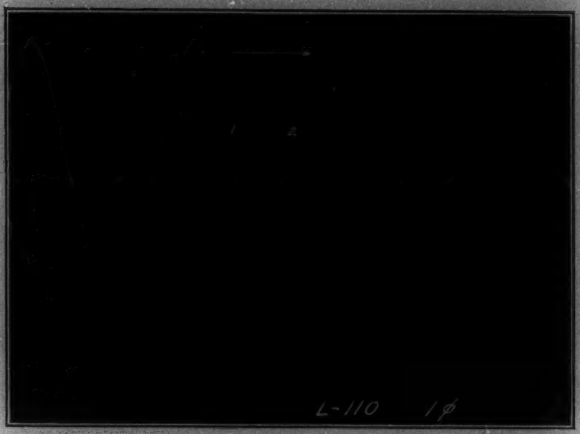


FIG. 6—POTENTIAL, FLUX AND CURRENT WAVES. STAR-STAR-STAR CONNECTION

is not materially different from that of the star-star connection which did not distort the generator voltage.

Fig. 9 shows the exciting currents for a star-delta connection of transformers. The third harmonic of the exciting ampere-turns is now derived from the high-tension delta circuit. The low-tension line current contains an excess of the fifth harmonic as in the previous case, causing the same flat-topped wave of voltage to neutral or delta voltage as before. The transformer and line voltages are given in Fig. 10.

For a delta-delta connection of transformers, the voltage distortions are apt to be increased, due to the troublesome



[CURTIS]

FIG. 1—EXCITING CURRENT AND POTENTIAL WAVES

Single-phase connection. Curve 1, voltage across transformer, 110.0 volts. Curve 2, exciting current, 2.00 amperes.

[CURTIS]

FIG. 4—EXCITING CURRENT WAVE

Star-star-star connection.

[CURTIS]

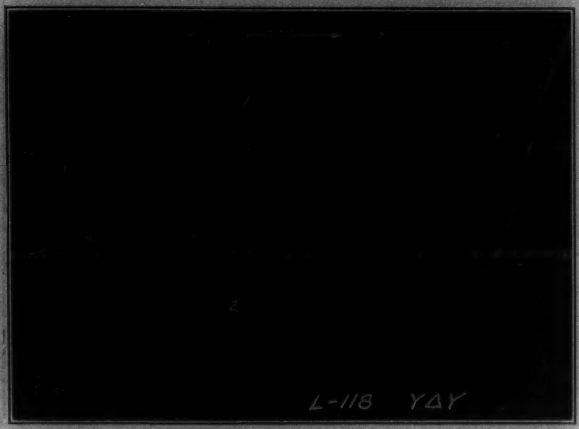
FIG. 5—POTENTIAL WAVES

Star-star-star connection. Curve 1, voltage to neutral, 121.0 volts. Curve 2, voltage between lines, 190.3 volts.

[CURTIS]

FIG. 7—EXCITING CURRENT WAVES

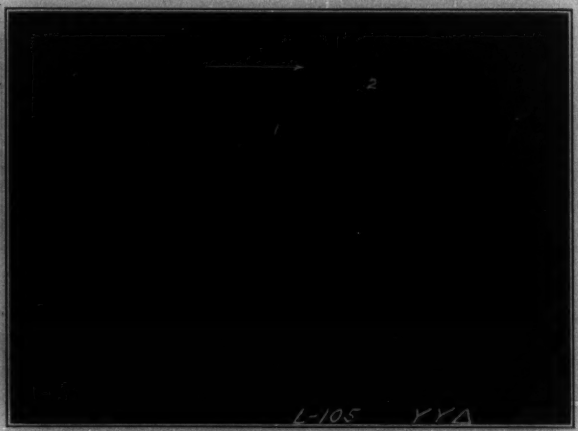
Star-delta-star connection. Curve 1, line current, 3.39 amperes. Curve 2, transformer current, 2.11 amperes.



[CURTIS]

FIG. 8—POTENTIAL WAVES

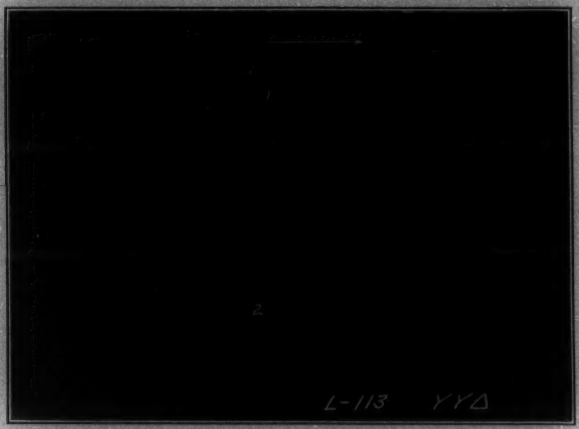
Star-delta-star connection. Curve 1, line voltage 1924.0 volts. Curve 2, delta voltage 110.0 volts.



CURTIS]

FIG. 9—EXCITING CURRENT WAVES

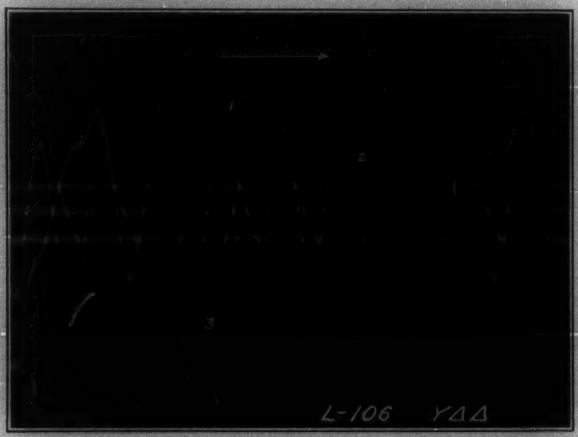
Star-star-delta connection. Curve 1, delta current. 0.074 ampere. Curve 2, line current, 1.94 amperes.



[CURTIS]

FIG. 10—POTENTIAL WAVES

Star-star-delta connection. Curve 1, voltage to neutral, 110.0 volts. Curve 2, line voltage, 190.3 volts.



[CURTIS]

FIG. 11—EXCITING CURRENT WAVES

Star-delta-delta connection. Curve 1, line current, 3.49 amperes. Curve 2, high-tension delta current, 0.068 ampere. Curve 3, low-tension delta current, 2.15 amperes.

[CURTIS]

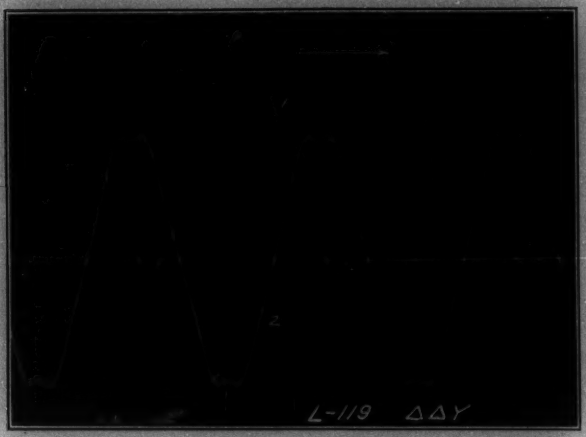
FIG. 12—POTENTIAL WAVES

Star-delta-delta connection. Curve 1, voltage to generator neutral, 63.8 volts. Curve 2, line voltage, 110.0 volts.

[CURTIS]

FIG. 13—POTENTIAL WAVES

Delta-star-star connection. Curve 1, voltage to neutral, 121.1 volts. Curve 2, line voltage, 190.3 volts.



[CURTIS]

FIG. 14—POTENTIAL WAVES

Delta-delta-star connection. Curve 1, line voltage, 1930.0 volts. Curve 2, delta voltage, 110.0 volts.

[CURTIS]

FIG. 15—POTENTIAL WAVES

Delta-star-delta connection. Curve 1, voltage to neutral, 110.1 volts. Curve 2, line voltage, 190.3 volts.

[CURTIS]

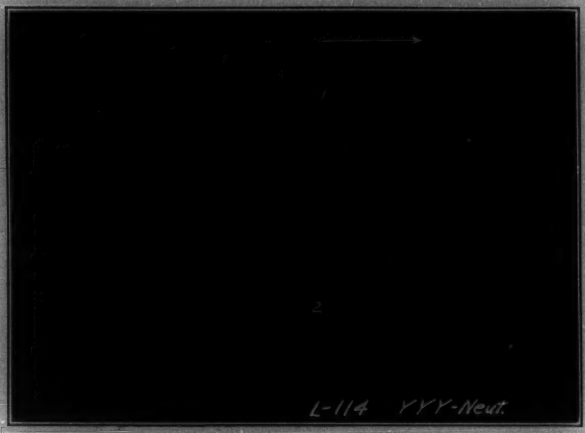
FIG. 16—POTENTIAL WAVES

Delta-delta-delta connection. Curve 1, low-tension voltage, 110.0 volts. Curve 2, high-tension voltage, 1110.0 volts.

[CURTIS]

FIG. 17—EXCITING CURRENT WAVES

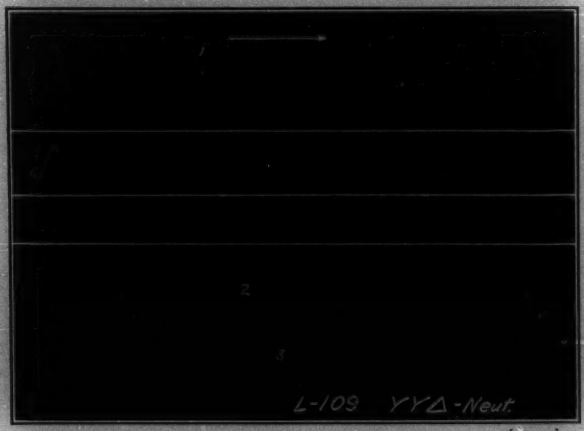
Star-neutral-star-star connection. Curve 1, neutral current, 1.83 amperes. Curve 2, line current, 1.99 amperes.



[CURTIS]

FIG. 18—POTENTIAL WAVES

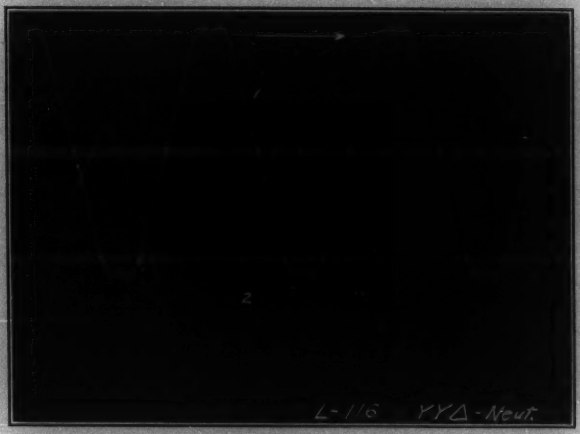
Star-neutral-star-star connection. Curve 1, voltage to neutral, 110.6 volts. Curve 2, line voltage, 190.3 volts.



[CURTIS]

FIG. 19—EXCITING CURRENT WAVES

Star-neutral-star-delta connection. Curve 1, neutral current, 3.55 amperes. Curve 2, delta current, 0.186 ampere. Curve 3, line current 2.23 amperes.



[CURTIS]

FIG. 20—POTENTIAL WAVES

Star-neutral-star-delta connection. Curve 1, voltage to neutral, 110.2 volts. Curve 2, line voltage, 190.3 volts.

fifth harmonics in the exciting circuits. The currents and voltages for this connection are shown in Figs. 11 and 12.

Tests with Delta-Connected Generator

With the generator connected in delta, the short-circuit third harmonic current in the armature produces a pulsation at six times the normal frequency in the field flux, which, in turn, introduces a fifth and a seventh harmonic in the armature voltage. Of these, the fifth is the more troublesome, producing the familiar flat-topped wave of delta voltage.

Distortions due to the transformer connections are superimposed upon the generator wave. Figs. 13, 14, 15 and 16 show the voltages of the banks of transformers connected in star-star, delta-star, star-delta and delta-delta respectively, when excited from the delta-connected generator. The original wave form of the generator voltage is shown in Fig. 13, since the star-star connection of transformers does not distort the line voltage.

Tests with Connected Neutral

When the generator and the low-tension side of the transformers are connected in star with connected neutral, the third harmonic components of the exciting current may return to the generator over the neutral, each phase constituting a single-phase circuit.

The waves of exciting current for a star-star bank of transformers with connection to the generator neutral are shown in Fig. 17. The voltages are shown in Fig. 18, being very nearly sine waves.

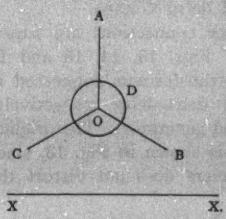
If the high-tension side is now placed in delta, there exists a short circuit of the unbalanced third harmonics in the three transformers. This causes an excessive third-harmonic current to flow over the neutral which reacts upon the generator flux in the same way as that in a delta-connected generator. This is shown in Fig. 19. A flat-topped wave of voltage to neutral and a peaked line voltage result, as shown in Fig. 20.

Preferable Connections

From the above results it is seen, from the standpoint of wave form, that the banks of transformers connected delta-star, star-delta, or star-star with connected generator neutral give the best results. The latter connection would be ruled out if dissimilar banks were to be operated in parallel.

DISCUSSION ON "THE EFFECT OF DELTA AND STAR CONNECTIONS UPON TRANSFORMER WAVE FORMS" (CURTIS), SPOKANE, WASH., SEPTEMBER 9, 1914.

P. M. Lincoln: We may represent a three-phase system as in this diagram, in which the figure *ABC* may be assumed to rotate around its center *O*. The instantaneous voltages will then be proportional to the lengths of the projections upon a line, as *XX*. For instance, at the instant represented in the figure the instantaneous voltage of leg *AO* is zero, that of phase *CB* is a maximum, and those of phases *AB* and *AC* are each one-half of the maximum, one increasing and the other decreasing.



If we so represent a three-phase system, we will find that a third harmonic in the leg voltages *OA*, *OB* and *OC* will have the effect of causing the neutral point *O* to rotate around the small circle *D* and the rate of rotation of the neutral around this small circle will be three times that of the whole system around *O*. For instance, if we assume that the point *A* has advanced 10 deg., during the same time the neutral will have advanced 30 deg.

The diameter of the small circle *D* is dependent upon the amount of third harmonic that enters the leg voltages *OA*, *OB* and *OC*. It is evident from this analysis that we may have any amount of third harmonic voltages in these leg voltages without having any third harmonic voltages in the phase voltages *AB*, *AC* or *BC*. This physical conception has enabled me to see this problem more clearly than otherwise and I pass it on for what it is worth.

L. J. Corbett: The paper appeals to me as a very valuable one and one which requires a great deal of study. It brings to light some very interesting problems and I think this idea as given out by our president is very valuable. It is a new one to me. I thought at first he was referring to the unbalancing of load which has the effect of shifting the neutral on this three-phase triangle.

A. A. Miller: It seems to me that this question is open for discussion by the representatives present of the faculties of the several universities and also by the operating engineers. The effect of the oscillograph upon the ability which we have to diagnose these cases is very marked. Some half-dozen years ago there was absolutely nothing of the kind to assist us; the effects of the higher harmonics were guessed at and such results as were acquired, were obtained by means of curves which were plotted more or less from a theoretical basis. By means of this

highly sensitive instrument which we now have, we can see exactly what goes on in these circuits.

E. G. Robinson, Jr.: What results are gotten with open-delta connections? I think that is a connection that a great many of us are using to start with on our transformers for power and light; and the question arises in my mind, what is really taking place in your transformers regarding the circulating currents, the triple harmonics and the circulating current in the delta where this delta is open; were these secured with a delta closed or the delta with one side open? I start with an open delta in my transformers and as my load increases, or my power load increases, I close my delta. I would like to have the author answer that question regarding the circulating currents when using transformers with open delta.

M. H. Gerry, Jr.: The old question has arisen of the relative advantages of delta and star connections for power transformers. No general conclusion has ever been reached in this matter, nor is there likely to be any definite answer, as there is no one controlling condition or set of conditions. Certain practises have arisen which have worked well in particular situations. In other places different practises have seemed best. There are so many things to be considered that, after all, the question is one of general expediency.

L. T. Merwin: Along the line of a suggestion already hinted by Mr. Gerry I ask Mr. Curtis, in closing, to answer this question—What form of connection is advisable from the standpoint of the operating engineer for protection of the transmission line beyond the power house, say for voltages ranging from 60,000 and up? The operating engineer is particularly interested in wave forms as well as circulating currents at two points, one between the generators and transformers at the power house and the other between transformers and line. And then again, what bearing has the wave form upon the breakdown point of his transmission line after it has passed beyond the power house? Will the star-delta or the star-star or the delta-star connection give the safest form of wave curve on the line from the standpoint of the breakdown? It is that which interests particularly the operating engineer. Mr. Curtis shows his oscillograph curves with transformer connections open on the high side; but with load on the end of a 150-mile high-tension transmission line, what changes in the wave form will take place as against an open transformer bank?

Livingston P. Ferris: I ask Mr. Curtis to cover the following points in his closure: Just what wave form is considered in the comparisons upon which you base your conclusion? By what criterion do you judge the distortion of wave form characteristic of the different types of connections? Have you followed the recently adopted standardization rules of the Institute or some other standard?

I will mention two circuit arrangements for oscillograms

which have been found useful in the investigation of the Joint Committee on Inductive Interference in California. These circuit arrangements are designed to distort the wave form of current through the vibrator, magnifying the higher harmonics in this wave as compared with their relative magnitude in the desired main line current or voltage wave. For current waves, the secondary of a current transformer is closed through a low-impedance air-core inductance coil, the constants of one such coil being $1.12 + j\ 0.0468\ f$ ohms. Around this coil is shunted the vibrator of the oscillograph in series with a condenser and rheostat. The amplitude of the wave and magnification of the harmonics in the vibrator current are controlled by adjustment of the condenser and rheostat in series with the vibrator. An analysis of the vibrator wave expressed in current units, together with a knowledge of the circuit constants, enables one to compute the value of the main line current corresponding to any harmonic. Care is necessary with this arrangement, in order that the impedance in the secondary of the current transformer shall not be too high and particularly that the circuit shall not resonate at or very near the frequency of some harmonic which it is desired to measure. For voltage waves, the vibrator is connected in series with a condenser and rheostat and supplied from a potential transformer. By these methods of accentuating the higher harmonics the accuracy of their determination in the current and voltage waves is much increased.

H. V. Carpenter: I would like to enlarge a little on the point that Mr. Curtis brought out, that the various connections which he dealt with give different losses in the transformer cores. That would have some bearing in determining the capacities of these different connections, the load capacities. It might be possible if Mr. Curtis has given the matter any thought to tell us something about the amount of increase in rating that might be considered possible in certain cases over that of other connections. It would seem from the hysteresis diagrams which he showed that there might be sufficient saving in core losses there to make it appreciable in the load capacity of the transformer sets.

L. F. Curtis: As to Mr. Robinson's question regarding the open delta, I regret that I have no oscillograms for this connection. I will predict that there will be an unbalance of voltage between the three phases. There could be no third harmonic in any current flowing over a balanced three-phase line, but if there is an unbalance, as would be the case with open delta excitation, there might be a diversity of third harmonic components in the different lines. This would probably produce a reduction of voltage across the open phase, causing the voltage triangle to become distorted, the shortest line representing the voltage across the open side. It would also be probable that the wave forms of voltage of all three phases of the two transformers would be different. It is quite probable that if one wave were flat the others would be peaked.

As to Mr. Merwin's question: Papers which were presented at Pittsfield made similar reference to the subject from a practical standpoint. From my observations, the wave forms are the best upon the lines with the star connection of transformer windings and connected generator neutral, but this connection is possible only when the transformer banks are not operated parallel with others of different characteristics. If such parallel operation were attempted, as has been in some cases, circulating currents between the banks would flow over the neutral, causing heating which should be prevented. It appears to me that the best connection would be a star-connected generator, delta-connected low-tension circuit, and star-connected high-tension circuit, with possibly a grounded neutral, the advantages of which were pointed out in the papers presented before the Institute at Pittsfield in May. The wave forms for this connection are good.

We know that an inductive load tends to flatten the higher harmonics and that the wave forms with the inductive load would then be much better than without it. The most serious disturbances would probably occur on an unloaded line, because of the fact that the capacity of the lines exaggerates the higher harmonics in exact proportion to their order in the charging current. If we have, for instance, an eleventh harmonic on the line of say ten per cent. it appears in the charging current or capacity current as ten times eleven or 110 per cent, so that upon the line open at the far end we would expect the greater distortion and the most trouble from the higher harmonics. During switching we may have other disturbances due to the fact that the three phases are not closed simultaneously, and as noticed from the experience on the California lines, less trouble from switching seems to be caused when a grounded neutral with a star-connected high-tension circuit is used.

As to the criterion for judging wave forms: I have not used the American Institute standard because it tells nothing of the order of the harmonics. In analyzing the waves, I have kept a record not only of the effective and maximum values of each wave, but the per cent and order of each harmonic, so that due weight might be given to the harmonics of higher order. I might say that in these investigations, none above the fifth was objectionable. I used the connection suggested by Mr. Ferris, that of the condenser in series with resistance for exaggerating the harmonics in the voltage waves. Upon the generator used, the fifth was the only noticeable higher harmonic in the voltage wave. The tests were run throughout without any transmission line connected, so that effect of capacity in the high-tension circuit may be neglected. It was a no-load test throughout.

As to the higher rating of the star-star-connected transformers because of the change in core loss, I think that this rating would be affected very little and would not be the criterion. In the

star-star connection the core loss is only a small percentage less than for single-phase. The rating of the transformer would be slightly greater, but on account of the objectionable voltage to neutral, the connection would probably be ruled out in any case.

It is to be regretted that the paper is incomplete in that the author has been unable to deal with the wave forms of three-phase transformers. With three-phase shell-type transformers, the results would be very similar to those obtained with the three single-phase units, but with three-phase core type units, the wave shapes would be considerably changed.

Since the recording of wave-shape was considered to be of prime importance, no special care was taken to calibrate or correct meter readings. Portable instruments of the electrodynamometer type were used for voltage readings. For the measurement of potential upon the high-tension windings a potential transformer was introduced. Care was taken to disconnect all potential-reading-instruments before taking current oscillograms. While the tests were not made with great scientific accuracy, uniform conditions were maintained throughout, making the results in the different cases comparable.

Presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Spokane, Wash., September 10, 1914.

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150,000-VOLT TRANSMISSION SYSTEM

Some Operating Conditions of the Big Creek Development of the Pacific Light & Power Corporation

BY EDWARD WOODBURY

Abstract of Paper

The paper describes operating conditions on the 150,000-volt transmission line of the Pacific Light and Power Corporation which delivers power from the Big Creek hydroelectric development to Los Angeles, Cal., 240 miles away. In daily operation 60,000 kw. are generated, utilizing a total hydraulic head of 4000 ft., in two steps. Plans for the future contemplate the building of two more power houses, operating under somewhat lower heads.

Of particular interest is the complete success of the constant potential system, *i. e.*, operation at the same voltage at the generating and receiving stations, by means of synchronous condensers at the receiving end, in conjunction with automatic voltage regulators, one for each condenser as well as for the generators at each of the power houses. The line has been operated with unusual freedom from short circuits.

Appendixes describe the development of the system, and give data relating to the equipment of the Big Creek transmission line.

THE most striking feature of the Big Creek development and transmission is the magnitude of the figures in which the plant data are expressed. In daily operation, 60,000 kw. are generated, utilizing a total hydraulic head of 4000 ft. (1219 m.) in two steps, and transmitted 240 miles (386 km.) at 150,000 volts, thus entailing some conditions of operation which are rather striking.

The transmission line is of course the element of greatest importance in satisfactory commercial operation, although there are many features of engineering interest in the generating and receiving parts of the system.

The most critical problem to be solved proved to be that of regulation. It must be remembered that the inherent regulation of the line alone, without terminal equipment, is from 10 per cent above power house voltage at no load, to 20 per cent below at full load; that the effect of the transformer inductive

reactance at the generating end practically doubles the boosting at light load, and that the self-exciting characteristics of the generators, when supplying charging current only, tend to produce abnormal voltages at light load.

The complete success of the constant potential or zero regulation system, *i.e.*, operation at the same voltage at the generating and receiving stations, is of particular interest. This result is obtained by the use of synchronous condensers at the receiving end, in conjunction with automatic voltage regulators, one for each condenser as well as for the generators at each of the power houses. Since there are two 15,000-kv-a. condensers and four 17,500-kv-a. generators to be controlled, the regulator problem received most serious consideration, and was made the subject of careful experiment under working conditions before being proved satisfactory, as it now is. It has been

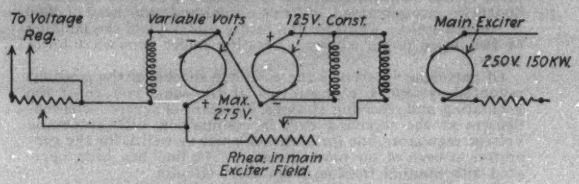


FIG. 1—EXCITER CONNECTION, PLANT NO. 1, BIG CREEK.

found necessary to arrange the regulators to control field currents from a maximum to zero.

In one generating station the excitation system consists of three direct-current units, one of which is the exciter proper, the other two being connected in series opposition, and used to excite the field of the main exciter. See Fig. 1. The two units making up the secondary exciter are designed to generate 125 volts and 275 volts respectively. With a potential regulator on the 275-volt unit, arranged with auxiliaries to prevent a reversal of the field in the 125-volt unit of this set, the voltage applied to the exciter field may be changed from that required to give maximum excitation to zero excitation, within a range of voltage on the 275-volt unit which can be readily handled by the standard alternating-current automatic voltage regulator.

The alternators at the other generator station are excited directly by 200-kw., 250-volt exciters, the main field of which

is controlled by a new type of alternating-current automatic voltage regulator, which has no direct-current magnet and which can therefore be adjusted to reduce the exciter voltage to zero. The exciters on this system have three shunt windings on the field, as shown in Fig. 2. One auxiliary field is provided to give the reversed excitation necessary to hold the voltage down when charging the line, the current being supplied to this field, through a variable resistance, by means of a storage battery. The other auxiliary field, which is solely for the purpose of maintaining the correct polarity, also takes its current, which is small, from the same storage battery.

A reduction of the excitation to zero by means of the potential regulator, has not been necessary at the generating stations, but operation of the synchronous condensers at the receiving

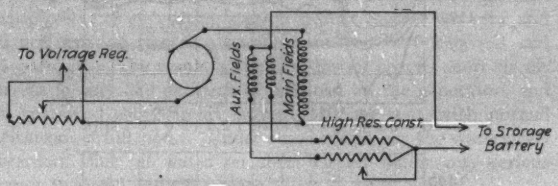


FIG. 2—EXCITER CONNECTION, PLANT NO. 2, BIG CREEK.

station, over the range required, would not be feasible without a complete reduction of the exciter voltage.

With 150,000 volts at the receiving end of the line, the charging current is about 40 per cent overload for one generator. With normal voltage of 6600 volts at the generator, the charging current overloads the generator 65 to 70 per cent. Hence in normal operation a line is usually energized by using two generators, under which condition a small field excitation in the normal direction is required. Abnormal conditions sometimes make it necessary to charge the line from a single generator, until the condensers at the receiving station can be started.

The self-exciting characteristics of the system with leading current are such that in one of the generating stations a single 6600-volt generator, when connected to an unloaded line without its condenser and run at normal speed with the field switch open, would excite itself to 7600 volts, corresponding to 190,000 volts on the transmission line at the generating station, and

demand from the generators 35,000 kv-a. and 3000 actual kilowatts.

At the other station, where the generators were designed by a different manufacturer and had slightly different characteristics, the results were greater and the self-excitation under similar conditions would reach 9000 volts at the generator or 230,000 volts on the line at the generating end. For this con-

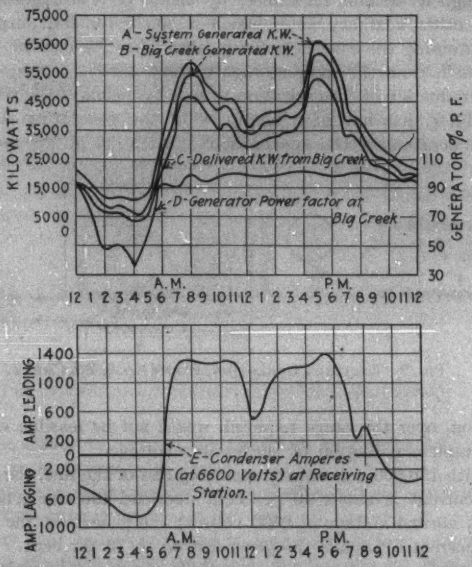


FIG. 3—TYPICAL DAILY OPERATING CURVES OF BIG CREEK SYSTEM, WITH ZERO LINE REGULATION.

dition the generator would have to deliver 5000 kw. and about 50,000 kv-a.

Means had therefore to be furnished for using current in a reverse direction in the generator fields to counteract the excitation due to the leading current.

The curves of Fig. 3 show typical daily operating conditions as follows:

(A) System-generated kilowatts.
(B) Big Creek-generated kilowatts.
(C) Delivered kilowatts from Big Creek.
(D) Generator power factor at Big Creek.
(E) Condenser amperes (at 6600 volts) at receiving station.

The difference between A and B is on account of other generating stations being in operation on the system and being used to the limit of their capacity for correction of load power factors.

The speed regulation by the waterwheel governor has been excellent, so that no complications have arisen from this source.

As might be expected with a system of this magnitude, special consideration has been given to minimizing the effects of short circuits. Accordingly, the reactance of the generators of the two manufacturers has been made 70 per cent and 85 per cent respectively; of generating station transformers 5 per cent and 8.5 per cent; of receiving station transformers 5 per cent and 8.5 per cent. The result is that the instantaneous short-circuit current is only 330 per cent of full load on the generators and the sustained short-circuit current 110 per cent, with normal excitation, of full load. Under these conditions the waterwheel governors shut off water on short circuit before any serious change in speed can take place.

On account of the use of aluminum cable for the transmission line, it is very desirable to suppress an arc on the line before the wire can be seriously injured; and there is now under consideration the installation of a field-killing relay to be installed in the neutral of the generating station transformers, which will very quickly extinguish the arc and automatically permit the restoration of voltage immediately.

Of the short circuits which have occurred, none have been sufficiently serious to burn down the cable. Some of the outer strands have been scorched, but not sufficiently so to diminish strength. The scorched sections are of course removed at the earliest opportunity.

The causes of the short circuits, which have occurred, may be stated as follows:

1. In the rush of construction, a tree was left standing too close to the line and blew against it. The cable was scorched, but not seriously hurt. This occurred during the tryout period, and while the voltage was returned to normal in a fraction of a minute, the load was transferred to the steam plant, for some

time, while experimenting was done to endeavor to locate the trouble.

2. An irrigator tried to clean out a well near the line with a heavy charge of dynamite, blowing a lot of mud and water into the line. The current arced to the ground cable, but did not seriously injure the transmission cable.

3. One of the insulators on a disconnecting switch in one of the stations flashed over.

4. Seven other line short circuits have occurrred, five of which have been found to be due to flash-over of insulators, one to be due to an arc from line to a tree during high wind, and the location and cause of the other has not been discovered. In every case of the above, trouble was cleared by reducing the voltage at generators upon current being observed in the ground ammeters, after which service was immediately resumed.

In all cases of insulator flash-overs, the damage to insulators was so slight that service could be resumed, without repairs, immediately on extinguishing the arc. In two cases, two disks out of the string of nine were broken down or badly shattered. In the third case, two of the disks were slightly chipped on the edge.

In the remaining two cases the arcing bars with which the insulator hardware is furnished (see Fig. 4), protected the insulators against any damage. It is found that a flash-over will sometimes burn from one to two inches off the end of the arcing bar, and apparently does not go to the cable unless the direction and strength of the wind are such as to carry the arc out along the cable. The separation of the arcing bars is 51 in. (129.5 cm.), equivalent to a break-down potential of over 500,000 volts at normal frequency.

5. The most serious line interruption was caused by a mechanical defect in a dead-end clamp at the end of a 2700-ft. (823-m.) span across a wide and deep river. The weight and tension of the cable make a repair of this kind a serious matter. The clamp which failed was one out of 5000, so the percentage is not high.

Various features of the system have been described in detail in different technical journals and do not need repetition, but, for convenience, appendixes follow, showing how the growth of the Pacific Light and Power Corporation system made an installation of the magnitude of Big Creek an economic possibility, and giving the principal physical data of the develop-

ment. The author desires to thank Mr. H. A. Barre and Professor R. W. Sorensen for their generous assistance in the preparation of this paper.

APPENDIX I

HISTORICAL

In 1897 the San Gabriel Electric Co. built at Azusa a hydroelectric plant consisting of four 300-kw. generators, which received their energy from a small stream with a 400-ft. (122-m.) head. The water power converted into electric energy by these generators at a potential of 500 volts was transformed to a potential of 15,000 volts and transmitted at this potential a distance of 25 miles (40 km.) to Los Angeles. Later, four other small hydroelectric plants varying in size from 150 kw. to 1500 kw. were added, and a "standby" steam plant of 2000 kw. was constructed, giving a total capacity of 6000 kw., 4000 kw. of which was water power.

January 1, 1905, the Kern River plant, a hydroelectric plant made up of five 2000-kw. generators, which transmitted its energy over 125 miles (201 km.) of line at a potential of 60,000 volts, was developed, and two years later, the original Redondo steam plant, which at that time made such a record for efficiency, was completed and its 15,000 kw. contributed to the service of the community. Even this, however, was not sufficient, for in 1911 it was found necessary to add to Redondo two 12,000-kw. turbine units, thus bringing up the available capacity of the system to 55,000 kw.

Even this tremendous supply of power rapidly became insufficient to meet the demand, and the company prepared to carry out the development of the now famous Big Creek project, which was to convert the energy available in Big Creek into electric energy and transmit it 240 miles (386 km.) to Los Angeles.

To transmit electric energy over such a distance with economy requires, of course, the highest practical potential, which in this case was selected as 150,000 volts, and plans for transmission at this voltage were drawn. These plans called for the immediate development of 60,000 kw. maximum, delivered at this voltage to the Los Angeles receiving station known as Eagle Rock substation.

This energy is generated by four 17,500-kv-a., 6600-volt

generators, two in each power house. At Power House No. 1 the water is delivered to the wheels under an average head of 2050 ft. (624.8 m.) from a reservoir about five miles (8 km.) long and one mile (1.6 km.) wide, with sufficient storage capacity to operate the plant at full load about four months, which is equivalent to six or eight months of operation based upon a 60,000-kw. peak on the two plants. After leaving Power House No. 1 the water enters a second tunnel, whence it is carried 4½ miles (7.2 km.) to Power House No. 2, where it is delivered at an average head of 1857 ft. (565 m.).

Projected Development

Each of the two present power houses is so designed that its capacity may be doubled, simply by raising the height of the storage dam and installing the necessary generators, waterwheels, transformers and switching equipment. Future plans contemplate the erection of two other power houses, each as large as No. 1 and No. 2 will be when completed, at a lower elevation. These will operate under a somewhat lower head than power houses No. 1 and No. 2, but the difference in head will be supplemented by the addition of more water.

Construction

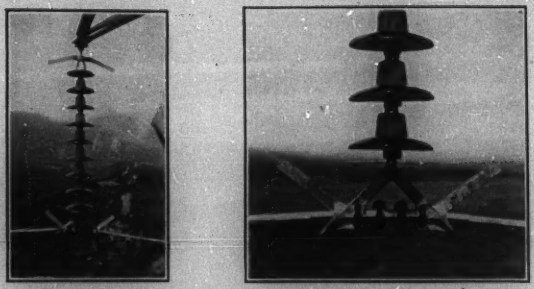
In order to take up the construction of the Big Creek project, it was necessary to construct 56 miles of standard-gage railroad over a very mountainous country, where even with the many curves the average grade is over 4 per cent. Materials were hauled over this track to the power house sites with shay locomotives, very often three engines being applied to a four-car train of heavy machinery.

It was also necessary to build two inclined railways, one to transport material from the end of the railway to the reservoir site and one to let material down to power house No. 2 from the railroad. When the work was at a maximum of activity 3500 men were employed, all of whom were housed in fifteen camps located in the mountains a long distance from supplies.

APPENDIX II

Equipment Data

Two power plants, total capacity 64,000 kw.
Four 17,500-kv-a. generators.
Eight tangential waterwheels, each pair develops 16,000 kw.



[WOODBURY]

FIG. 4—150,000-VOLT SUSPENSION INSULATOR, SHOWING ARCING RODS.

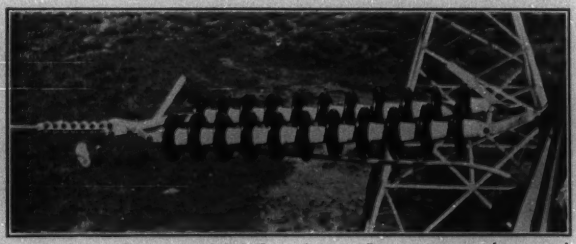
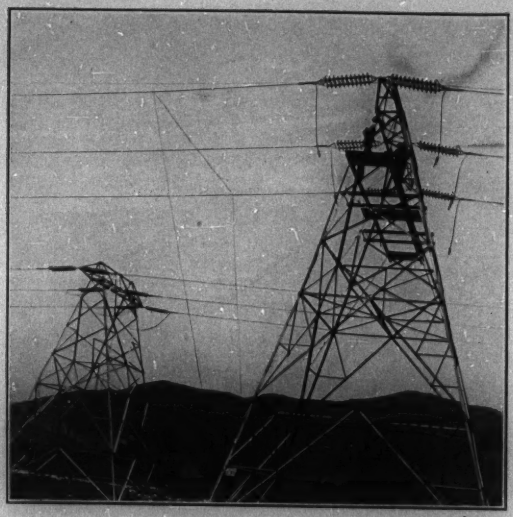
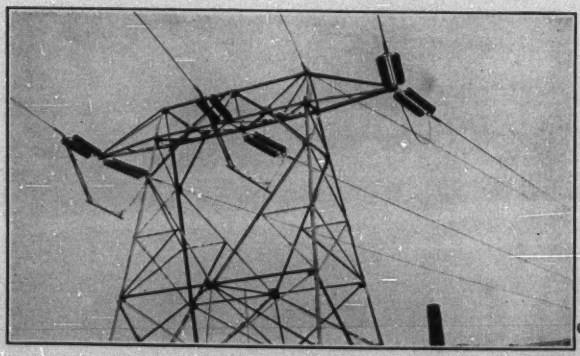


FIG. 5—150,000-VOLT STRAIN INSULATOR. [WOODBURY]



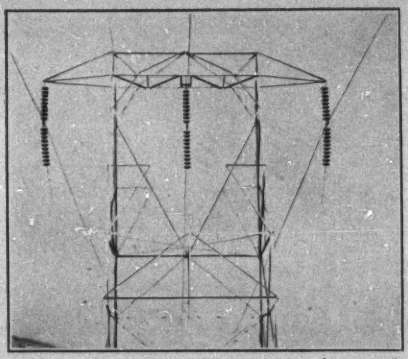
[WOODBURY]

FIG. 6—TYPICAL DEAD-END TOWER USED FOR LINE SECTIONALIZING BY OPENING JUMPER LOOP.



[WOODBURY]

FIG. 7—ANGLE TOWER, SHOWING BRACKET TO PREVENT LOOP FROM SWINGING.



[WOODBURY]

FIG. 8—METHOD OF TYING DOWN CONDUCTORS TO PREVENT UPLIFT IN COLD WEATHER.

[WOODBURY]

FIG. 9—STEEL FOOTING FOR STANDARD TOWER.

One generator, full load, 24 hours, uses 240 acre-feet of water.
Maximum head of water, plant No. 1, 2100 ft. static. Plant No. 2, 1900 ft.
Reservoir capacity, initial development, 51,600 acre-ft. Cubic yards concrete in dams, initial development, 120,000.
Reservoir will operate plants 220 days on 50 per cent load factor.
Drainage area 88 square miles.
Five miles of 12-ft. tunnels through solid rock.
Single-phase transformers, largest yet built, weigh 81 tons and contain 10,000 gal. of oil.
Power station transformers connected delta 6600 volts, Y 150,000 volts, with grounded neutral.
Receiving station transformers connected delta 150,000 volts, delta 60,000 volts and 18,000 volts respectively.
Two 15,000-kv-a. synchronous condensers at receiver end each require 10,000 kv-a. to start.
Under no-load conditions, 137,000 volts at generator rises to 150,000 volts at receiver.
Charging current is 90 amperes at 137,000 volts, equals 21,500 kv.-a.
Fifty amperes reversed excitation necessary to bring generator "down on line" to zero potential, no-load condition.
Power factor of generators is high, being above 95 per cent the greater part of the day.
Current is unbalanced approximately 12 per cent under no-load conditions on account of the conductors being in horizontal plane.
Under normal load conditions, this 12 per cent is reduced to approximately 2 per cent.
A potential of 4200 volts is induced in a dead section of the duplicate line 100 miles in length, distant 82 ft. center to center.
Line loss at full load is 9 1/2 per cent. In addition there is 5 per cent loss in transformers, auxiliaries, etc.

Data on Big Creek Transmission Line

General:

Length, 240.41 miles power house No. 1 to Eagle Rock substation, plus 0.74 mile tap to power house No. 2, total 241.15 miles.

Voltage, 150,000 volts, 50 cycles.

Number of tower lines, 2.

Number of circuits per tower line, 1.

Capacity of each circuit, 57,500 kw. at 0.85 power factor for 11 per cent regulation, using two synchronous condensers.

Right of Way:

Width of right of way, 150 feet.

Separation of center lines of tower lines, 82 ft.

Towers:

Normal spacing in valleys where no sleet occurs, 660 ft.

" " " " " sleet occurs, 550 ft.

Maximum span, 2871 ft. (Sunland), 2776 ft. (Kings River).

Maximum span on standard towers, 1822 ft.

Maximum angle on standard towers, 0 deg. 49 min. (Normal span no sleet 1 1/2 deg. plus wind). Insulators take 45 deg. position.

Maximum angle on anchor towers, 48 deg., designed for 60 deg.; 114 deg. 2 min. under special conditions at tower No. 1.

Total number of towers, both lines, 3388.

Average number of towers per mile, single line, 7.08

Classification	Standard	Anchor and Angle	Special
Weight above foundation.	4300	6450	4485
Weight of steel footings ..	1305	1605	1305
Total steel per tower.....	5605	8055	5790
Spread at base with line.	20 ft.	24 ft.	20 ft.
" " " across line	18 ft.	24 ft.	18 ft.
Height above ground to insulation support....	43 ft.	37 ft.	43 ft.

Unit Stresses:

Tension = 20,000 lb. per sq. in.

$$\text{Compression} = \frac{16{,}000}{2} \text{ lb. per sq. in.}$$

$\frac{L}{R}$ for corner posts, 125.

$\frac{L}{R}$ for bracing, 175, except where a larger value is approved by the purchaser.

Minimum thickness of members, 3/16 in.

Unit stress in bolts:

Shear.....15,000 lb. per sq. in.

Bearings.....30,000 lb. per sq. in.

Design Assumptions:

Standard Towers:

(1) Wind load, 22 ½ lb. per sq. ft. of exposed area, with or at right angles to the line; wind pressure simultaneously applied to both faces of tower, and

(2) A pull in the direction of the line of 4250 lb. at the points of support of two adjacent conductors pulling on the same side of the tower, and

(3) A vertical load of 1000 lb. at each conductor support where conductor is unbroken, and of 530 lb. at each ground wire support, and of 500 lb. if conductor is broken, and

(4) A wind load of 600 lb. at right angles to the line at each conductor support where conductor is unbroken, and of 300 lb. at right angles to the line at each conductor support where conductor is broken, and of 500 lb. at each ground wire support.

The above loads are simultaneously applied.

Ground wire support designed to withstand an unbalanced pull of 5000 lb. in the direction of the line.

Anchor and Angle Towers:

Anchor and angle towers are designed for each of the following groups of conditions, only one of which groups is to be taken at a time:

I. (1) A wind load of 22½ lb. per sq. ft. of exposed area, with or at right angles to the line; wind pressure applied simultaneously to both faces of tower, and

(2) A pull in the direction of the line of 8000 lb. at each of the three conductor supports, on either side of tower, and of 8000 lb. at each ground cable support, and

(3) A vertical load of 500 lb. at each of the three conductor supports and of 265 lb. at each ground cable support, and

(4) A wind load of 300 lb. at each of the three conductor supports, and of 250 lb. at each ground cable support.

II. (1) A wind load of 22½ lb. per sq. ft. of exposed area, with or at right angles to the line; wind pressure applied simultaneously to both faces of tower, and

(2) A pull at right angles to the line of 8000 lb. at each of the three conductor supports, and of 8000 lb. at each ground cable support, and

(3) A vertical load of 1000 lb. at each of the three conductor supports and of 530 lb. at each ground cable support, and

(4) A wind load of 600 lb. at each of the three conductor su pports and of 500 lb. at each ground cable support.

Number of conductors supported by each tower, 3.

Arrangement, in same horizontal plane.

Number of lightning ground wires, one at first; space for two if needed.

Smallest size angle iron used, 1¾ by 1¾ by 3/16 in.

Conductor:

Material, aluminum with steel core; steel double-galvanized.

Composition Metals	No. strands	Cir. mils	Weight per mile	Weight per foot	Elastic limit square inch	Ultimate tensile strength sq. inch
Aluminum.....	54	605,000	2940	....	13,000	26,000
Steel.....	7	78,500	1118	....	115,000	195,000
Total.....	61	683,500	4058	0.77		33,600

Total resistance 35 ohms per leg.

Maximum working tension allowed—13,000 lb. per sq. in. in aluminum.

Stringing tension at 80 deg. fahr.

Ice allowance.....3130

No ice allowance 4740

Type of joints, McIntyre sleeve on steel inside of compression aluminum sleeve.

Ground clearance:

On right of way.....25 ft. at 140 deg. fahr.

At crossings.....Legal, as required.

Ground Wires:

Number per tower, 1.

Size, ½ in. 7-strand.

Material, Siemens-Martin steel.

Breaking tension, 13,000 to 15,000 lb.

Maximum working tension allowed, 6500 lb. sleet—2100 ft. span; 5500 lb. no sleet.

Insulators:

Number, 190,000; 58 per cent of which are on dead ends.

Type, 2565-P Locke.

Diameter, 10 in.

Dry flash-over voltage.....	590,000 suspension 720,000 anchor.	9 disks
Wet flash-over voltage.....	420,000 suspension 420,000 plus anchor	

Routine Tests:

First test per disk, electrical, flash-over voltage.

Second " " " mechanical, flash-over voltage, 5000 lb., after first elec.

Third " " " electrical, flash-over voltage 5 min. after mechanical.

Ultimate tensile strength, 10,500 lb.

Maximum working tensile loading allowed, 4250 lb.

No. of disks used per chain, straight line, 9

" " " " " " dead end, 2 x 11 = 22.

Two chains are used in parallel on all dead ends to divide mechanical load.

Distance center to center of insulator, 5¾ in.

Two telephone circuits on an independent pole line 300 miles long. Resistance per circuit 4000 ohms. Storage batteries used on transmitters, and power-driven machines for ringing.

Eleven patrol stations are necessary, each requiring an equipment of tools and material weighing 10 tons.

DISCUSSION ON "SOME OPERATING CONDITIONS OF THE 150,000-VOLT TRANSMISSION SYSTEM OF THE BIG CREEK DEVELOPMENT OF THE PACIFIC LIGHT & POWER CORPORATION," (WOODBURY), SPOKANE, WASH., SEPTEMBER 10, 1914.

J. Harisberger: There has been considerable discussion as to the necessity of synchronous condensers on this system. I would like to know what actual practise in the operation of the system has brought out; could the system be operated satisfactorily without the use of synchronous condensers?

Mr. Woodbury's paper states that under conditions of short circuit the waterwheel governors shut off water before any appreciable change of speed can take place. I had the impression that the contrary would take place, that the governors would open up the gates.

I would also like to know if there are any transpositions in either of the transmission lines?

J. B. Fisken: One thing that struck me in listening to Mr. Woodbury's paper was the apparent success of the preliminary work. If all the work that Mr. Woodbury has told us of, has developed only the troubles he describes since the line was constructed, I think he is entitled to congratulations. I am reminded of an experience we had here eleven years or so ago when we first put into commission the line from Spokane to the Coeur d'Alene mines at 45,000 volts; none of us ever had the experience of seeing a line in operation at 45,000 volts; we didn't know what was going to happen, and inquiries were made as to what we should look out for. We were advised that all we had to do was to patrol the line and if the patrolman heard any insulators making any noise it was a sign they were defective. The noise was described as like the noise of frying steak. We energized the line and every insulator in that line sounded like frying steak, but there was not a single case of trouble; that of course was a comparatively low voltage.

It occurs to me that it might be possible to improve the operating conditions by adjusting the voltage so that for the greater part of the day the synchronous condensers might be cut out. The load factor is high, and I would like Mr. Woodbury to tell us whether it would be a practical operating proposition to cut out the synchronous condensers say from about six o'clock in the morning until eight o'clock at night. Of course, the only advantage of that is that it is a little less for the substation attendants to look after.

Another point on which I would like to hear some discussion is the method of tying down the conductors to prevent uplift in cold weather. In the line described by Mr. Woodbury, they use two strings, one of which would be in tension in hot weather and the other in tension in cold weather. In our tower line, we have only one short tower line, we use two dead-end insulators for the same purpose, and it would be interesting if we could get discus-

sion on that and try to formulate an idea as to which is the better one.

One other thing I would like Mr. Woodbury to tell us about; that is, whether they use any resistance or reactance in the ground connections or whether it is a dead ground.

A. A. Miller: I have one question I would like to ask Mr. Woodbury. He mentioned the fact that in the 100-mile section of transmission line an induced potential of 4200 volts exists to ground. How frequently is this 100-mile section grounded when repairs are being made, at one place or more than one place?

M. H. Gerry, Jr.: The achievement of operating a line at 150,000 volts is a most creditable one and indicates in a marked degree the great progress in electrical transmission made in the last twenty years. This is a comparatively short time for the development to take place from potentials around 2000 or 3000 volts up to 150,000 volts or even more. It was my good fortune to be connected with the transmission business during the early days, some seventeen or eighteen years ago. About that time we built a system in Montana and began operating at 50,000 volts. It was then impossible to get a manufacturer in this country to endorse that voltage or unqualifiedly guarantee the transforming apparatus. I remember that we made a compromise by arranging to drop to half voltage if anything serious happened. As a matter of fact, a good many things did happen, but nothing occurred to disprove the general principle that high voltage was desirable and essential for long-distance transmission of power. It is rather an interesting fact that high-voltage transmission was developed in the West; the reason being that it was essential to accomplish the results under the existing conditions, and for the further reason that Western engineers and Western men generally were free from prejudice and were accustomed to undertake problems and seek solutions without regard to what had been already accomplished, provided that there seemed to be no good reason why it could not be done. As I have already said, we constructed in that early day a transmission system between the Missouri River, near Helena, and Butte, a distance of about sixty-five miles, operating at 50,000 volts. This system transmitted a large amount of power and was a success from the start. A few years later the pressure was raised to 70,000 volts, and now in the same vicinity there are lines operating at 100,000 volts and transmitting power up to 150 miles. My experience with all these lines has been most satisfactory. The troubles were few and mainly of a mechanical nature. Of course it took several years to analyze the insulator problem and to determine the necessary conditions in that direction, but to-day there is practically no electrical trouble on transmission lines on the Montana systems. In our part of the country the transmission lines in places reach considerable altitudes, and I would be interested to know the maximum altitude reached on the lines described by Mr. Woodbury.

E. Woodbury. Five thousand feet.

M. H. Gerry, Jr.: In Montana the lines sometime reach altitudes around 7000 ft. In such high altitudes there is some evidence of loss at the highest voltages, but as it is local it does not affect the general result. Most of the transmission lines in Montana are of wooden pole construction up to about 70,000 volts; at higher pressures the lines are mainly on steel towers. A very large amount of power is handled in this section, the principal transmissions being from points near Helena and Great Falls to Butte and Anaconda. The principal load is in the form of induction motors but there are also a number of synchronous motors used for operating air compressors and direct-current motor-generator sets. Every conceivable kind of load is handled on the Montana system; power, railway, lighting and all kinds of industrial applications to which electrical current can be applied. All the lines and power plants are now in one great system and but little trouble is experienced with regulation or with interruptions of service.

V. H. Greisser: I would like to inquire of Mr. Woodbury whether any extended tests have been made regarding the distribution of potential on the separate units and across the string of units of the insulator, and in general what was found. Also whether any tests have been made regarding the question of what we might perhaps call aging of insulators.

E. Woodbury: Mr. Harisberger and Mr. Fisken and Mr. Fraser have all asked about the same questions, about whether or not the condensers were necessary. I think you will find in the first part of the paper it says that the inherent regulation of the line is from 10 per cent above to 20 per cent below power house potential. I think that the principal excuse for the condensers is the remarkable regulation that they afford us. With the condensers in the receiving station we hold the voltage exactly where it is wanted at all times of the day and night, without any reference to what the power house is doing. When we first started up, the telephone line was not complete and we operated for about thirty days without any telephone line, and we gave very good service. The two condensers are 15,000 kv-a. each, making 30,000 kv-a. of leading component, which is required a good part of the day. Now, that would have to be supplied elsewhere or else the power house voltage would have to be raised to about 175,000, which would be approaching the limits of corona loss.

The matter of using steam turbo-generators for condensers is quite feasible, as Mr. Fraser mentions, but with us we have the vertical type and of course it is out of the question to separate the generator from the turbine.

We are also informed that we should not run the turbines without having steam on them, so there is some expense to produce enough steam to keep them in operation even though they are carrying wattless current.

Mr. Fisken's question about not running the condensers from

6 a.m. to 8 p.m.—Now, that is the time we need them the most. This curve in Fig. 3 only shows the kilovolt-amperes of one condenser, because at that particular time the other condenser was shut down and turbines in the steam plant were supplying 15,000 kv-a. wattless component, so you can see that from about 7a.m. the condenser is up to almost 1300 amperes, which is 15,000 kv-a., and it runs right through with a drop at the noon hour; otherwise if we did not have the condensers the power house voltage would go up to 175,000 or so with the constant difficulties in regulation.

Mr. Miller's point about the line 100 miles or so long having 4200 volts induced potential—before we ground either end of that 100-mile section, we make a static voltmeter test to get the true potential, and find it 4200 volts, and when we ground the other end, it drops to about 500, and then we put another ground at this end. Also the linemen all have positive instructions to put their ground on before doing any work.

In regard to Mr. Greisser's question concerning the stress on the different units, we have never made any tests on that, but there were some made at the time the insulators were being manufactured when they were tested for flash-over, etc., and I don't know just what means they had of determining what the stresses were, but we got the report that the stresses were very uniformly divided, which does not seem to agree with some articles I have read and papers presented before the Institute. Of course, as to the aging of insulators, we have not been operating long enough to know about that, as we have been operating only about ten months. As to the mechanical stress, they will stand about 10,000 pounds and we use two strings in parallel, so that the stress is divided, about half of the stress is on each string, and normally there will only be about 5000 pounds altogether, only about 2500 on each string, but they will go as high as 8000 or 10,000 lb., so that would be 4000 or 5000 on each string. Long spans of course are strung the same as the short ones, all pulled up with the dynamometer to the same tension.

Presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Spokane, Wash., September 10, 1914.

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A DISTRIBUTION SYSTEM FOR POWER PURPOSES

BY F. D. NIMS

ABSTRACT OF PAPER

The paper describes the distribution system of the Western Canada Power Company, Limited, touching on the overhead and underground systems in general. It describes the advantages obtained by duplicating lines, both for eliminating outages and from a financial standpoint. Mention is made of the advantages obtained by using a steel-taped lead-armored cable placed directly in the ground, figures showing the exact cost of such an installation being given.

IN laying out a distribution system for power purposes primarily, instead of a lighting or combined power and lighting load, several differences are encountered which lead to a much simpler and less expensive system. It is my purpose to describe the system of the Western Canada Power Company, Ltd., of Vancouver, B.C., giving some of these points in detail.

This company has its power house at Stave Falls, B.C., about 35 miles (56.3 km.) east of Vancouver, distributing power to Vancouver and the surrounding districts. The power house is located nearly in the center of a somewhat sparsely settled district containing several fairly large industries scattered throughout it at a maximum distance of 18 miles (28.9 km.) from the power house. A line leads south to the international boundary at Sumas, Wash., where it feeds a line of the Puget Sound Traction, Light and Power Company, of Bellingham, Wash., supplying 5000 kw. at 60,000 volts. This line is wood pole construction, single circuit, with pin type insulators, the conductor being a No. 0 equivalent steel core aluminum cable. The average span is 250 ft. (76.2 m.) and the maximum 970 ft. (295.6 m.) Arm pins are of the saddle type, made of one-in. (2.54-cm.) galvanized channel iron, no bolts going through the arm. The two legs of the pin are bolted together just above and below the arm. On angles, a small lag is screwed into the arm as a heel. This type of construction is shown in Fig. 1.

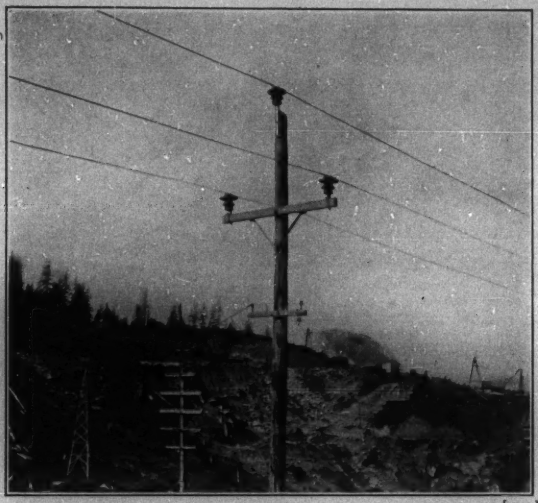
A steel-tower line, carrying two circuits of No. 0 hard-drawn

stranded copper with hemp center, runs from the power house for 33 miles (53.1 km.) to the receiving station at Ardley, located half way between the cities of Vancouver and New Westminster, and practically at the center of gravity of the industrial load. At Ardley, power at 60,000 volts is delivered to the British Columbia Electric Railway Company, Limited, which takes the current into Vancouver, where it parallels with that company's own system. Ardley station also steps the voltage from 60,000 down to 12,000, at which it is distributed to Vancouver, New Westminster and the surrounding district. The standard steel tower is shown in Fig. 2. On account of difficulty encountered from sleet and snow during the winter of 1912–13, the middle arm was extended, and Fig. 3 is a view of the same tower as it stands today.

All 12,000-volt lines are on wooden pole construction and carry, as far as possible, only one circuit to the pole, it being our belief that better service can be provided through making each circuit loop back to the transforming station by an entirely different route than to duplicate circuits on a single pole line; where more than one circuit is on a pole line they are generally considered and operated as a single unit. This method, by proper sectionalizing of the lines, reduces the chance of outage to a minimum, and when work is being done on the line, or stumps are being blasted, a short section can be isolated and killed so that linemen are absolutely protected from adjacent circuits; or if a piece of stump is blown into the line, no short circuit is occasioned which burns off the conductors.

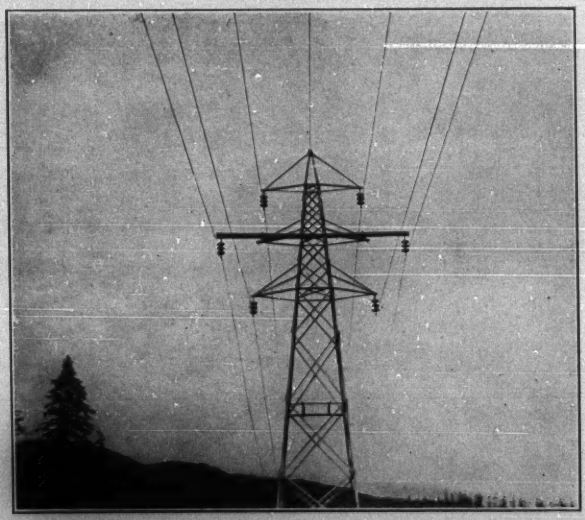
Aside from the power house and main receiving station, no substations are used, as there are no voltage regulators or similar apparatus which require attention. Transformers are generally placed on pole racks and operate as ordinary distribution transformers. Figs. 4 and 5 give a typical example of such a rack. It carries three 50-kw. transformers stepping from 12,000 to 2300 volts. Switches are either oil-break, pole type, or a combination fuse and disconnecting switch mounted on the pole. The company has designed and builds in its shop such a switch, which answers the purpose exceedingly well and costs very little.

Patrolmen are stationed at important switching points so that these switches may be operated quickly in case of emergency. Fig. 6 shows an installation of three 333-kw. 12,000- to 2300-volt water-cooled transformers in the outskirts of the city of Vancouver. These transformers are indoor type so that



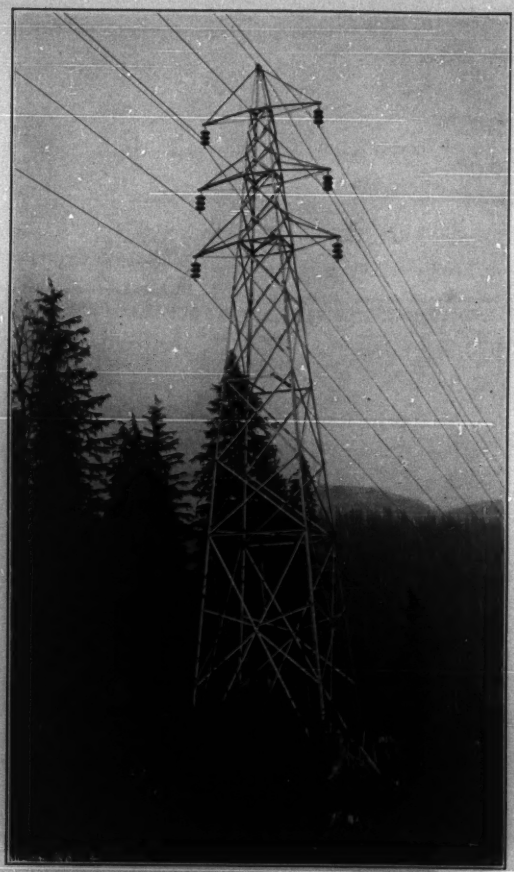
[NIMS]

FIG. 1—POLE ON BELLINGHAM 60,000-VOLT LINE, SHOWING SADDLE TYPE ARM PIN



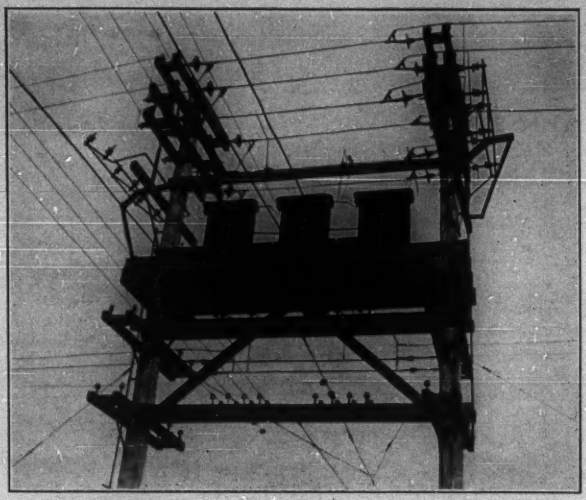
[NIMS]

FIG. 3—STANDARD STEEL TOWER WITH CENTER ARM EXTENDED



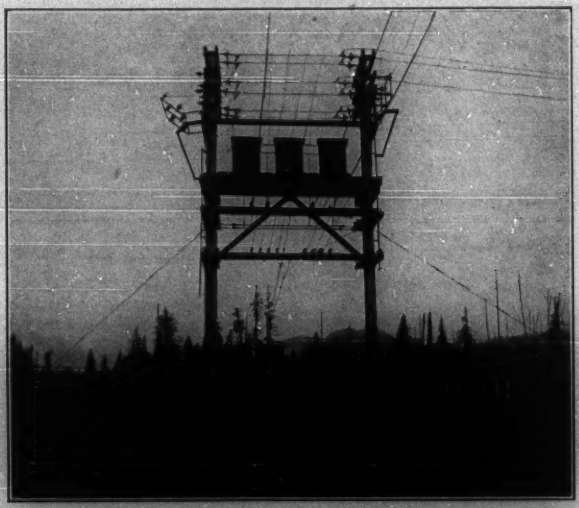
[NIMS]

FIG. 2—STANDARD STEEL TOWER WITH GROUND WIRE ON APEX



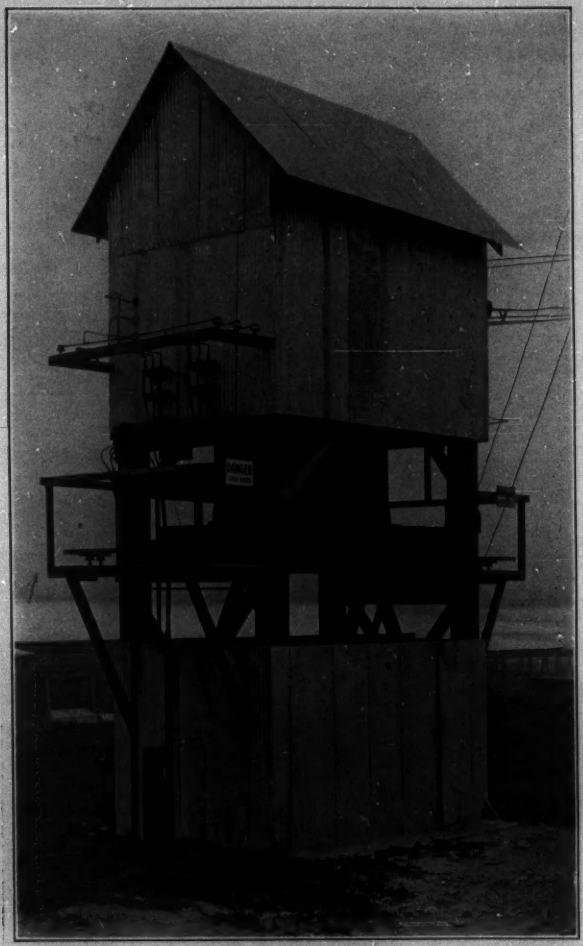
[NIMS]

FIG. 4—OPEN AIR RACK CARRYING THREE 50-KW. TRANSFORMERS, 12,000—2300 VOLTS. OPERATED WITH POLE-TOP SWITCHES



[NIMS]

FIG. 5—ANOTHER VIEW OF SAME RACK



[NIMS]

FIG. 6—RACK CARRYING THREE 333-KW., 12,000—2300-VOLT WATER-COOLED INDOOR TYPE TRANSFORMERS

[NIMS]

FIG. 7—CABLES SHOWING ONE END READY FOR JOINT

[NIMS]

FIG. 7A—JOINTS WITH CONNECTORS SOLDERED

[NIMS]

FIG. 7B—JOINT WITH ONE END WIPED TO LEAD SHEATH OF CABLE

[NIMS]

FIG. 7C—STRAIGHT JOINT BOX, PARTLY FILLED WITH BITUMEN, READY FOR COVER

[NIMS]

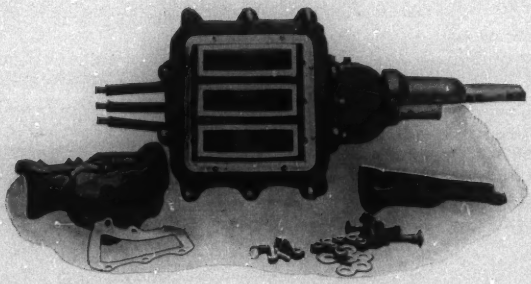
FIG. 7D—JOINT COMPLETED

[NIMS]

FIG. 8—TEE JOINT HALF FULL OF BITUMEN

[NIMS]

FIG. 9—SECTION BOX IN PLACE AND OUTER FORM READY FOR POURING CONCRETE



[NIMS]

FIG. 10—SECTION BOX SHOWING PORCELAIN COMPARTMENTS AND COPPER LINKS

it was necessary to roof them over with galvanized sheeting. Water for cooling is taken from the city mains. The view is from the 2300-volt side, showing the disconnecting switches, outdoor type oil switches, cable terminals and cables with their pipe protection. A patrolman, who lives in the vicinity, visits the station periodically and adjusts the flow of water through the cooling coils. In some cases, where a mill or factory has sufficient electrical apparatus of its own to warrant the employment of a skilled electrician, water-cooled transformers are installed in a small galvanized iron building. In short, the entire 12,000-volt system is handled in the same manner as a 2300-volt system, except that a circuit must be killed for a man to work on it.

Distribution in the cities of Vancouver and New Westminster is at 2300 volts by means of steel-taped and lead-armored cables laid directly in the ground, without conduit or other protection, except where crossing railway tracks or busy streets, where wood duct is laid to facilitate the pulling out or replacing of a cable without interruption to traffic. A trench is dug 30 in. (76.2 cm.) in depth, and of a width corresponding to the number of cables to be laid, (cables in place are from 4 to 6 in.—10 to 15 cm.—apart) the cable is reeled out and dropped directly into the trench. Joints are made by joint boxes, which cover the same character of joint that is made in the ordinary lead-covered cable, the space between the lead and the box being filled with ordinary bitumen, the box serving as a protection to the lead and also clamping the steel armor on both sides of the joint, providing electrical conductivity in the steel as well as mechanical strength in the cable as a whole. Fig. 7 shows five views of making a straight joint; the first showing the cable with one end ready for the joint, the armor having been stripped back, the lead cut back and the conductors separated. Fig. 7A shows the joint as made with copper sleeve connectors. Fig. 7B shows the joint with one end wiped to the lead sheath of the cable. Specially refined bitumen is poured through the holes in the lead sleeve after the ends are wiped, and the holes then capped with lead. Fig. 7C shows the straight joint box, itself, with the cover off, half full of bitumen, and Fig. 7D the completed joint. Fig. 8 shows the lower half of the joint box in the trench. Taps are made in a similar manner by means of a three-way box. At frequent intervals section boxes are placed in the line, these boxes being 18 in. (45.6 cm.) below ground level in a small manhole, or, more properly, handhole.

These holes have, as a bottom, a pad of concrete on which the box rests, the walls being circular and of cast iron; the entire hole being 26 in. (65 cm.) in diameter. The walls are flanged to take an ordinary cast manhole plate, which is used as a covering, these being flush with the street. Fig. 9 is a section box and hand hole with the steel form around it ready for pouring concrete. After pouring, the form is slipped off and the earth tamped in up to the concrete. The box has a bolted top which can easily be removed, and the copper links, which are set in porcelain compartments, can be taken out by means of wooden tongs. These boxes are used to isolate sections of cable when necessary to make new taps or work on the live conductors in any way, and also as interconnecting links between various cables, giving as a result several rings or loops. Fig. 10 shows a view of one of these boxes before placing in the handhole. The bolted cover is removed, showing the porcelain compartments and the copper links. The bell is of brass with a lead sleeve wiped in which fits over the lead sheath of the cable and is then wiped to it. After the conductors are connected and the lead joint wiped the bell is filled with refined bitumen, through the plug holes left for that purpose. The split armor clamp is also shown on the right side of the box.

Distribution transformers are placed either in vaults on the customers' premises or on poles, in which case the cable is carried to the top of the pole, where it terminates in an outdoor type terminal. Secondaries may be carried either back down the pole in the same kind of cable or run overhead to the building. Where cables run up the poles an additional protection is given by means of an iron pipe through which the cable runs. This pipe extends to a point about ten feet above the ground.

The question of cost on such an underground system must be taken up in each individual case, for it will vary a great deal with the quality of soil, cost of labor, probabilities of taps, extensions, etc., but it may be said, in general, that in places where it is not required to lay more than four cables in a trench, the steel tape cable, laid directly in the ground, will be found to be cheaper than any of the other systems. As a typical example of actual costs the following gives an idea, the figures being taken from a job carried out in Vancouver during 1911-1912.

Size of Cable	Amount laid, feet	Cost per ft., cents	Total cost
No. 00	73,336.6	52.24 to 62.18	$44,319.26
2	560.0	42.5	238.00
6	1,071.3	29.6	317.10
TOTALS	74,964.9	60 cents average	$44,874.36

Pulling cable (including splicing straight joints) $0.04 per ft.				2,992.69
Trenching				
Unimproved streets	28,224.2 ft. @ 0.50 cts. per lin. ft.	14,112.10		
Macadamized	13,207.9 " @ 0.58 " " "	7,660.58		
Plank walk	1,190.2 " @ 0.58 " " "	690.32		
Concrete walk	261.1 " @ 0.95 " " "	248.04		
Wood block (con. base)	6,547.7 " @ 0.95 " " "	6,220.32		
Brick Do.	203.0 " @ 1.05 " " "	213.15		
Stone Do.	4,302.2 " @ 1.10 " " "	4,732.42		
Bitulithic pavement	1,095.8 " @ 1.15 " " "	1,260.17		
TOTALS	55,022.1 0.632 average			35,137.10
74 straight joint boxes	@ $14.90			1,102.60
15 Tees	@ 22.90			343.50
4 Outdoor terminals	@ 29.00			116.00
2 Inside terminals	@ 10.15			20.30
8 End bells				10.00
Labor on terminals & joints (Not st. joints)				409.04
6 railway crossings (matl. 140.22 Labor 94.86)				235.08
96 street crossings (matl. 2440.18 Labor 1437.25)				3,877.43
Additional excavation for changes in grade				439.49
Moving building material etc.				294.70
15 section boxes, labor and material				2,250.00
TOTAL COST				$92,102.29

Cost per ft. of cable $1.23
Cost per mile of cable $6483.84
Feet of cable per ft. of trench 1.36
No overhead charges or engineering are included in the above.

Operating troubles have been few and far between, there having been, during two years' operation, but three cases. Two of these were caused by city workmen making sewer excavations taking the cable for the root of a stump and chopping into it with an axe or pick. On one of the pieces of cable so damaged we found the marks of 13 blows before the axe cut through to the conductor. The third case was a faulty joint at a section box which broke down the day after it was placed in service.

A complete card system is kept containing records of all cable locations, joints, etc., and we installed our own hubs in the streets as markers, the city hubs not being well defined.

This cable is practically a submarine cable, and in fact we have one length of 1500 ft. (457 m.) crossing the Pitt River, which has now been in service for two years without any trouble. The bottom on which it lies is fine silt or sand and there is a four-mile current caused by the tide. In another case it was necessary to cross a railway yard to furnish power to a pump located about 1000 ft. (304 m.) from the factory of the consumer,

the motor driving the pump to be controlled from the factory. As the expense of excavating for the laying of a cable would have been excessive and there was already a 12-in. (30.4-cm.) water main running from the pump to the factory, the cable was pulled in the pipe, the inlet and outlet of the cable being made through stuffing boxes. This has also proved very satisfactory.

The cable is composed of stranded conductors insulated with paper, the three conductors being insulated again with paper as a unit before the lead is put on. In most of the cable in this installation the conductors are sector-shaped, so that there are no spaces to be filled with jute or other material and a smaller over-all diameter is obtained, for a given size, than is possible with the round conductor, thus requiring less lead, steel and jute, and making a cable lighter in weight. The lead sheath is $\frac{1}{8}$ in. (3.1 mm.) thick and over this is wound jute yarn impregnated with tar. Outside of this jute are wound, in the same direction, two layers of mild steel tape 0.039 in. (1 mm.) in thickness and 1.5 in. (37 mm.) in width, so laid as to break joints. Over this tape is again wound yarn impregnated with tar. The over-all diameter of such a cable in three-core No. 00 for 4000 working voltage is about 1.75 in. (34.5 mm.).

One of the most important factors in the use of a cable buried directly in the ground, instead of being in conduit, is the ease with which heat can be radiated. Although the amount will vary somewhat with the character of the soil, it is safe to say that on this account an increase of approximately 15 per cent may be allowed in the current-carrying capacity over that in conduit. Exhaustive tests on this subject are now being carried out.

In regard to the life of a cable installation of this sort, nothing definite can be said as yet. The writer has personal knowledge of a large installation which has been in service in volcanic soil in the City of Mexico since 1900, and no perceptible deterioration has occurred, except where exposed to extreme electrolytic action, and in these cases it had a much longer life than lead cable in conduit in the same vicinity, due to the steel tape acting as a protection.

DISCUSSION ON "A DISTRIBUTION SYSTEM FOR POWER PURPOSES" (NIMS), SPOKANE, WASH., SEPTEMBER 10, 1914.

J. B. Fisken: It was my good fortune last year at the Pacific Coast Convention at Vancouver to see quite a good deal of the work that Mr. Nims had done with this ductless cable. I have noted some of the points on which I would like to hear some discussion. These are: the relative cost of ductless and duct lines, the use of the various insulations, such as paper, varnished cambric, and rubber, and the relative advantages of the wire of the shape he mentions as against round wire.

It appears to me that this system of ductless underground cable is eminently suitable for distribution in residential districts, but I don't see how it can be practicable in congested districts such as the business part of the various cities where you might have as many as thirty or forty cables in one duct line; it would appear to me that there would be many operating difficulties—or, rather, maintenance difficulties in keeping such a lay-out as that in commission.

P. M. Lincoln: This matter of the kind of cables that Mr. Nims is using is probably the most interesting point in the paper.

I ask first if he has any difficulty in locating faults and if he can locate them so that he does not have to dig very much when he comes to find the fault and repair it; also I presume that this type of installation would not be at all applicable where you have to take up pavement to make repairs—in that case I presume it would be out of the question.

The question which Mr. Nims mentioned, of this being much more capable of getting rid of heat, is an important one. When the Niagara Falls plant was installed 2200 volts was the voltage and it was considered high at that time—1893-4;—those were 3740-kv-a. generators, and there were ten of them, which gave a whole lot of current to take care of. That current was distributed to our various customers at 2200 volts and it was distributed through cables in ducts, and the problem of getting rid of the heat in those ducts was at that time and still is one of the most difficult problems which has to be dealt with. I can assure you that any means of increasing the capacity of the cable, so far as the heat is concerned, appeals to me on account of my experience there. We made many duct conduits in the early days, some of them as many as 36 ducts, and we found the cables in the middle of those many-duct lines would have an exterior temperature rise of 50, 60 or 70 deg. fahr. to begin with, some of them more than that, so that you can see that the problem of getting rid of the heat, particularly the heat in those conductors which ran in the interior ducts of the conduit, became a very serious one. They have even gone so far as to circulate water in some of the ducts in order to get rid of the heat. This is really an important problem, particularly where large amounts of power have to be dealt with at relatively low voltages.

F. L. Rohrbach: Regarding the cost of underground systems

which would include a duct and manholes, I do not think there is any question but what Mr. Nims has used the cheapest method in his system at Vancouver; but I ask Mr. Nims if he has considered the case of using ducts and leaving out manholes (except those necessary for switching); also the use of lead-covered cables, and what that would mean. I suppose this cable could be exposed at points where the manhole would naturally be built, so that in case of trouble it will only mean digging down at each manhole, or where the manhole should be, and pulling out the cable that is in trouble. It would mean also that you could watch the size of your cable; and when necessary it would be easier to take out a small cable and replace it with a larger one. Now, I do not know exactly the difference in cost between this steel-armored cable and lead-covered cable, but judge it would be about ten cents per foot, that is, for the same size cable used with the steel armor and cable used in duct. Where you have three ducts in one line, they can be laid cheaper than three lines of single duct—I would figure the saving in cable roughly at ten cents a foot; thus lead-covered cable would be probably $7,300 cheaper. Another place you could save would be in the cost of the straight-joint boxes; that would be $1100 over the other method, as I understand these boxes are a means of connecting the armor on each side of the lead sleeve and keeping it continuous.

I do not understand the items under the "six railway crossings" and "ninety-six street crossings." There are no lengths given and I have no idea what the total distance is. If they are ordinary streets of 75 or 100 ft. it seems to me the cost is high, as I understand that is where the wooden duct was installed. Of course I know nothing about the labor costs in Vancouver, but here in Spokane I would estimate that a single fiber duct surrounded with concrete could be installed for about sixteen cents per duct foot, and wooden ducts for twelve or thirteen cents. Of course my idea in installing this lead-covered cable, in a duct throughout the whole system, as well as at crossings, is simply for the purpose of being ready to pull out in case of trouble; and I think Mr. Nims will find that if there is a breakdown in the cable there will be some difficulty in locating the point of trouble. I have found that a good many Eastern companies in testing for trouble use what they call the "cut-and-try" method. That does away with any complex test. Most of them simply go out and cut the cable probably at the center and find out which half it is in and then trace it back. I think this would probably be the case at Vancouver, although there may be some other method of doing it. There is one method which is used by simply putting a current on the conductor that is in trouble and then reversing the current. You go along in each manhole with a compass held close to the cable, and when you come to the point where your compass does not vary, you have passed the point of trouble and you know which section it is in; but you would be unable to do that with armored cable.

I suppose that Mr. Nims has certainly considered the conduit and manhole construction, and if he has I would like to hear approximately what the difference was in his estimates, and also if he has considered the duct alone, leaving out the manhole, because it would be a simple question to leave a four-foot section and have your joints there so that you could easily get down and uncover your cable. Of course I understand that by doing this you would have to cut your cable up in smaller pieces, have more joints, but you would get rid of making your additional joints over your lead-covered cable which you do with these straight joints. I think that here in Spokane I could come pretty close to this total cost, and put in a single duct, leaving out the manhole.

There is another question: Mr. Fisken said something about a large number of cables. I think it would be entirely out of the question to put in many cables; in fact, I do not know but what four would be too many, and especially as the size of the cable is not stated; for it would depend entirely upon the size of the cable. When you get a cable from about 1.2 inch to 1.7 inch the additional cost of the armor runs up considerably, varying from ten cents if the lead sheath is 1.2 inches in diameter, up to 19 or 20 cents, going up very rapidly to 1.7. The cost of the duct in fiber (fiber and cement) is about 16 cents; that is not including the trenching because I have taken for this estimate that the trenching, is already done; I have only taken the cost of installing the duct, which will run from probably 16 cents down to 10 cents, depending on the number of ducts. A wooden duct would be cheaper, possibly from fourteen down to seven or eight cents.

The amount of heat dissipated by this cable is placed approximately at 15 per cent over one working in a conduit. I would like to ask Mr. Nims if he has made this test, whether it is between armored cable in a duct and armored cable in the ground, or whether it is between armored cable in the ground and lead-covered in the duct. The additional insulating (jute) over the armored cable would probably cause an increase in heat of seven or eight per cent; that is, it would be harder to get rid of the heat due to the doubling, practically, of the insulation.

And regarding electrolysis, there is no question that the armor would be some protection against electrolysis, but still if electrolysis was present the armor might give way and the lead would possibly be eaten up, or if electrolysis was not sufficient to eat away the armor it probably would not injure the lead so quickly.

C. S. MacCalla: I had a little indirect experience some years ago in the system which was in the city of Sydney, Australia. The New South Wales government owns and operates the street railways in Sydney, which is a city of about three-quarters of a million; I happened at that time to be working for an American contractor who was installing a three-phase generating

apparatus and substations. The cable was placed by an English contractor; it differed from Mr. Nims's cable and was considerably inferior to it; it had no iron armor and no insulation outside other than a little bitumen. The cables were laid in open trenches, I think about as many as eight in a trench, and were surrounded with a bituminous material and covered with treated plank. This cable was installed some months before the generating apparatus was ready for operation, and when they came to put the current on we had all kinds of trouble; and when investigated it was found that electrolysis had destroyed a large portion of the cable. If I had been the operating man at that time I would have been very thankful for a few ducts to pull out the cable. The whole city, which was largely paved, had to be dug up, the streets were torn up for some time, and the system had to be practically relaid.

H. V. Carpenter: I have had a little experience along this line, and I might state one instance which shows the durability of the steel armor. We have one cable line across the college campus, in which the cable is laid about two feet underground; during the excavation for our new engineering building recently they got over the line too far, and I found them tugging away at the cable with a plow and team, but they hadn't damaged it, so we moved it over out of the way. The cable showed no injury at all. It seems to me that in cases of that sort, where it is in a park or some place where there is no pavement, and there is no danger of electrolysis or any of those things, the use of the buried cable is very satisfactory.

Regarding the location of faults, I would like to say that the system which is now in use quite commonly by water companies, for locating troubles in pipes, could be used for locating faults in this cable. That is, put a current through the cable to the point where the fault occurs, and then take a coil with a good many turns on it and connect up the telephone receiver, walk along the ground over the cable, find the fault and dig it up and fix it.

P. M. Lincoln: About that last-mentioned method of locating faults—I have had some experience with it. That very same scheme was tried by the Niagara Falls Power Company back in about 1896 or 1897, and the trouble we found was that the location of the fault thereby was not definite. There would be at the point of the fault a slight diminution of sound in the telephone, but you would hear the telephone still buzzing for five hundred feet beyond the fault, and we found that the location of the fault was so indefinite that we had to abandon that scheme and locate our faults by some other method.

H. V. Carpenter: I think the accuracy with which that location could be made would depend considerably on whether het inductive coil was working by electrostatic action or by electromagnetic. If a current of sufficient strength is put through the cable to the point where the fault is located, so that

the action is not electrostatic, then the trouble would be located quite accurately.

P. M. Lincoln: The influence of the cable upon the telephone is due to electromagnetic induction entirely, and the difficulty was undoubtedly due to the fact that the current, after it left the fault, followed the cable and got away into the ground rather gradually and the telephone would not distinguish whether the current flowed in the copper conductor or in the lead sheath.

Edward Woodbury: The paper states: "Water for cooling is taken from the city mains." I wonder if they waste that water or whether they attempt to save it. We have a small pump and cooling tower and the water is circulated; then for an emergency we have a city supply and in case the motor stops running the city water is turned on automatically.

G. B. Rosenblatt: Regarding water-cooled transformer substations, I wonder whether, where Mr. Nims comes from, they have any trouble with their cooling system from freezing. The matter of climatic conditions might be of further interest. I wonder how much freezing of the ground they have to contend with when they have any repair work to do in winter on the cable system.

John Harisberger: The use of cables in trenches without ducts appeals to me, especially as to first cost, if it is not intended to make numerous connections.

The problem of cooling water for transformers has confronted most operating companies. Use of city water is expensive, and a cooling tower is not a perfect arrangement. We have a rather novel arrangement in our Everett substation to prevent the waste of water. There are two pipe lines, one at 125 pounds pressure and one at 80 pounds pressure. The water for the transformer cooling coils is taken from the 125-pound line through a reducing valve which reduces the pressure to 90 pounds, and is discharged into the 80-pound line. This arrangement has proved quite satisfactory.

One of the gentlemen mentioned a cut-and-try method for locating trouble in cables. I wonder if Mr. Nims had any facilities for sectionalizing his 60,000-volt overhead lines, such as pole-top switches. If pole-top switches are used, has he found them satisfactory?

L. J. Corbett: This paper relates to the actual engineering features of an installation for a definite purpose. We can appreciate a difference between the installation for power alone, and one for both lighting and power. When the lines are opened temporarily or the voltage fluctuates due to some heavy load coming onto a system of the latter class, there may be a good deal of trouble caused, and complaints will be heard from the lighting customers. On a purely power load the fluctuations are not so noticeable, and while shut-downs may cause inconvenience, this is not comparable with a similar one on a lighting system, and for these reasons certain economies can be effected

in the installation of such a system. Going still further, there are yet other systems which take greater liberties. In the case of a private manufacturing plant, for instance, which is generating or even buying its power and distributing it through its own system, liberties are sometimes taken with standard construction which would not be considered at all by a power company serving an exacting public. In Mr. Cotton's address which was given yesterday, we heard the term "near confiscation." We have in such cases as these at times a condition of "near unsafeness," and the limit is quite often approached rather closely.

I recently had occasion to make an estimate upon a system to use steel-armored cables, and found the cost to be somewhat more than that of lead cable and iron pipe conduit. The difference was not great, but it appeared to me to be in the wrong direction.

As has been brought out, quite frequently tests are made so closely that one can locate a fault within a very few feet, if the data regarding the length of line, distances, etc., are definitely known. In one or two of the cases just mentioned where the coil and telephone receiver were not successful, it occurs to me that possibly the reason for not locating the fault more closely might be this: If you have a large number of cables in a set of ducts, only one of which is faulty, your instrument will not be so sensitive as it would be in a case where there is but one cable, as in the campus system mentioned by Professor Carpenter.

Paul Lebenbaum: Relative to the advantages of sector as against round conductors, I know of an instance in which an operating company had a duct line that carried the maximum size of cable using round conductors, the number of ducts being limited by physical conditions. It being necessary to increase the capacity of this line, without resorting to a new route, cables of the sector type, having the same outside diameter as the round type, were substituted for the latter, and the desired increase in capacity was thus obtained.

E. Woodbury: I ask Mr. Nims if a sector cable costs more than the ordinary round type.

H. W. Carpenter: I ask how small size the sector cable is that is used; it occurred to me that if the sizes were carried down too low the corners of conductors would offer considerably greater tendency for electrostatic stresses to break through the insulation there than you would get with the round section.

F. L. Rohrbach: There is one company that I know of which does not recommend making a sector cable in which the conductor is less than 1/0. They claim that conductors smaller than 1/0 are apt to cause too sharp bends or points, which introduce the corona effect and sooner or later cause the cable to break down. This same company recommends an "oval" rather than a "sector" cable, especially for the smaller sizes.

These odd-shaped cables were first introduced for the purpose of saving duct space, and were therefore made in the larger sizes. For example, a 4/0 three-phase 15,000-volt ordinary cable is as

large as you can install in a 3½-inch duct, but by making a "sector" or "oval" cable, you can probably increase the conductor to 350,000 cir. mils. For my part, I can see no reason, but rather an objection, for making a small size cable in these special shapes. My objection would be that you decrease the circumference of the lead sheath, and thus cut down the radiating surface. I think this cable used at Vancouver was made in "sector" shape mainly to hold down the cost of the armor.

M. T. Crawford: I ask Mr. Nims what types of lightning arresters are used on the 12,000-volt lines of the system and what operating success has been secured. On 13,000-volt distributing lines for rural light and power on Puget Sound we have in some cases installed horn gaps without resistance of any kind and set for about three times line voltage. This type of equipment is only installed on the ends of branch feeders into rural districts where it has been necessary to keep the cost of construction down. Electrolytic lightning arresters are invariably used on the busbars in the distributing station. As the 13,000-volt feeders frequently run underneath 55,000-volt lines for some distance after leaving the station, there is the possibility of accidental contact between circuits, as well as the trouble from lightning to care for. A short circuit on the ends of these light capacity 13,000-volt lines will only trip the circuit breaker and cause a short interruption, which is preferable to damaging distributing transformers. I should like to hear other engineers' ideas on this subject.

F. D. Nims: There is one portion of the paper which apparently I have not made sufficiently clear. At the bottom of page 1302 you will find it stated "Where it is not required to lay more than four cables in a trench, the steel tape cable, laid directly in the ground, will be found to be cheaper than any of the other systems." This does not mean to indicate that I would advocate the use of steel tape cable in all cases. In fact, for more than four cables in a single trench I would probably put in a conduit system of some sort. I have a very vivid recollection of having trouble in a lead of 28 cables running out from a central station and the difficulties we experienced in tracing out the cables.

We find in testing for faults that the number of cables in the trench determines to some extent the accuracy with which we can find that fault. There is one method of testing which we are using at present which has not been mentioned, and that is by the bridge-megger. We find that with this on a 2/0 cable we can locate within about 130 feet. We isolate the section of the cable which is in trouble by means of the section boxes and test from both ends of the faulty piece. By this means we generally run our trouble down to within 75 or 80 feet. If there is a joint in the vicinity or if any digging has been going on we look at that first, but if nothing of this sort occurs we open our trench near where the fault is located and test with

the "telefault." We find this instrument very good when we can get close to the cable with the exploring coil, but we cannot work it satisfactorily through twenty or thirty inches of earth.

As to repairs where cable is under the pavement; we have very little difficulty with that. After locating it requires a hole possibly three feet square to get down to the cable. The manholes or section boxes are used only for sectionalizing a cable or for cross-connecting cables. Everything is run out from the step-down transformers in rings or loops.

In regard to the street crossings and railroad crossings mentioned here, I will say that labor at the time the job was going on was costing $3.00 per 8-hour day. The duct under railway crossings, under the British Columbia laws, must be in concrete and that runs the cost up considerably. I will state in answer to Prof. Carpenter's question that No. 6 is the smallest conductor we use and very little of that; almost entirely 0 and 00.

Using city water for transformers costs us for a thousand-kilowatt bank of transformers about $8.00 per month. We have practically no freezing weather in Vancouver.

I am unable to give any figures on the difference in cost between the sector shape and round conductor cable. At the time we purchased our cable we were unable to obtain a sector-shaped conductor anywhere in the United States or Canada, so bought in England, so that it came into Canada under a preferential tariff. Where we would have to pay full duty from the United States on round conductors, it is difficult to get a line on comparative costs. I believe that the sector-shaped cable is now being manufactured in the United States, but only recently.

As for pole top switches for 60,000 volts, there is very little difficulty in installing them on steel towers, but on our present installation the line is so short that we have had very little occasion to use them. In fact it has been so seldom that we have found it about as easy to open the loop at a strain tower.

Referring to Mr. Crawford's question regarding lightning arresters: Electrolytic arresters are provided on the 12,000-volt lines where they have the station, but in no other place. We run these lines in some instances on the same poles with the 60,000-volt lines, but do not consider that with good construction there is any probability of accidental contact, and believe that the possibility of such a contact is so remote as not to warrant expensive protection.

In regard to electrolysis I will say that we have had practically no trouble with electrolysis in Vancouver, so that really up there we do not know much about it. We had a good deal of trouble in Mexico City with electrolysis due to the poor bonding on the part of the street railway company, but, as I have mentioned in the paper, we found that the steel tape type of cable stood up very much longer than the straight lead cable placed in a conduit right alongside on the same street, one on each

side, originally laid by the two different companies which we took over. There was the same electrolytic action, but we pulled out the lead cable about three years before I left there, the steel tape cable remaining, and in those 3 years we had no electrolytic trouble. There was a slight electrolytic action on the armor, but not enough in any way to destroy its effectiveness. What Professor Carpenter said in regard to the strength of the cable we have found in several instances. I know we have had washouts and would have possibly 40 or 50 feet of the cable lying out with no support whatsoever, and would try to get into it with picks, try to hack it with axes, and all sorts of things, and it has been a pretty hard job to get through it.

We built a duct line, that is, going out of the station to the distributing system, at Mexico City. We had a fire some ten years or so ago when I first went there and my first job was to try and straighten out that tangle. When we tried to find out which cable was which it was almost hopeless, so finally while the service was interrupted we built a conduit run to take the cables outside the yard and got rid of the tangle.

Presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Spokane, Wash., September 10, 1914.

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ELECTRICITY IN THE LUMBER INDUSTRY

BY E. F. WHITNEY

ABSTRACT OF PAPER

The development in the application of electric drive to the lumber industry has been exceptionally rapid. Successful sawmill companies are now even operating entirely from central station service, notwithstanding the large amounts of refuse available for fuel.

The paper considers the lumbering industry as carried on in Washington and Oregon, and describes the application of electric power to the various operations carried on under the two main divisions of logging and milling. Typical applications are described, to illustrate types of motors and power transmission equipments, and the average power demands of the various logging operations and milling processes. In addition to the machines used in ordinary sawmill work, those used in planing mills and shingle mills are described. The question of the disposition of waste is considered, and comparative fuel values are given. The illustrations show logging operations and electrically driven saws, finishing machinery and lumber-handling machinery in the Pacific Coast lumber districts.

THE first comprehensive applications of electric drive in the different branches of the lumbering industry are of such recent date, and the individual installations vary to such an extent, that no general treatment of the subject could be undertaken until more well-defined practises were settled upon.

Not more than four years ago a completely electrically-operated sawmill was considered a hazardous undertaking; today, a new mill adopting other than the electric drive is the exception. The results of such operation have been so gratifying that today we can show two large and successful sawmill companies operating entirely from central station service, in spite of the large amounts of refuse available for fuel.

The first complete [illegible] operated mill was put in operation about 1908; the total installation consisted of 800 h.p. connected load, with a generating plant capacity of 600 kw. The first electric logging engine was put in commercial service in 1912. The electric railway used solely for logging purposes, is yet to come.

Before the above [illegible] many special machines—and often complete planing mills—were driven electrically, but none were

willing to pioneer such drives for the heavy duty sawmill machinery required for Coast conditions. There is necessary today but one further step, viz., a drive for the cumbersome log carriage that will compare favorably in first cost with the simple twin engine, and the necessity for steam will be entirely banished from the milling branch of the industry.

The lumbering industry, as a whole, must be divided into two distinct classes of work for our consideration: logging and milling.

Under the first heading we have the following operations: felling the trees: cutting to desired lengths: gathering from the woods: loading: hauling to distribution centers: unloading: sorting: rafting and towing.

Under "milling" come the manufacturing plants and their various processes, which must be divided into: saw mills: planing or finishing mills: specialty mills.

The Pacific Coast and Northwestern States, together with British Columbia, contain two-thirds as much standing timber as there is in the entire United States; Oregon contains approximately one-fifth, Washington one-seventh and California one-seventh. In lumber production Washington, Oregon and California rank, respectively, first, fifth and fourteenth and their combined output is one-fifth of the total cut of lumber in the United States. The sawmills alone in these three states require approximately 240,000 h.p. for driving their mill machinery. Further than this, in the two northern Pacific Coast states, viewed from the point of manufacturing industries, the lumber production is of even greater importance; for instance, in 1913 the value of the lumber mill output in Oregon was approximately one-third of the total value of the manufactured products in that state.

Logging

In the branch of the industry embraced under the heading "logging", progress in the application of electric drive was very slow. It is only of recent years that power-driven logging machines have met with general favor, displanting the old ox team. The flexibility of steam engines under the very severe demand imposed in such work, was thought to be an insurmountable obstacle to the adoption of any other system; for instance, the loggers demand an equipment which can stand very heavy overloads momentarily imposed and which, at the same time, has flexibility enough to allow the progress of the log to be stopped almost instantly should it encounter an obstacle.

At the present time it is estimated that there are approximately 3000 steam-driven logging engines in the two states of Washington and Oregon. Most of these outfits are twin-cylinder engines approximately 10 by 12 in. (25.4 by 30.48 cm.). The average operating boiler pressure is 160 lb. (72.5 kg.) gage, so that they have great capacity for intermittently imposed heavy overloads. From the viewpoint of electric operation this requires a motor which will seldom come anywhere near its continuous capacity, but which will frequently be called upon to exert its maximum torque.

In these two states the operating companies total 532, with an output of 7,080,000 M. ft. (board measure) or about 23,600 M. ft. (board measure) per day. The scene of their operations is often far removed from railroads; in the above operations the average distance from the scene of logging operations to the mill or to tidewater, varies from one to 35 miles (1.61 to 56.3 km.). The average distance is approximately 15 miles (24.15 km.). The maximum distance of which we have record that logs are handled by rail in either of these two states, is 120 miles (202.1 km.), and by towing—after reaching tidewater—125 miles (210.1 km.).

An added drawback to the use of electricity in the camps was discovered in the distance of the operations from the centers of power generation or present transmission lines.

Logging operators demand the simplest possible outfit, which necessitates the adoption of alternating current for such work.

The average cost to the logging company of logs at the boom is approximately $8.00 per M. ft. board measure. This is divided approximately as follows:

Fixed charges	17 per cent
Logging (including felling trees, gathering and loading)	50 " "
Hauling by rail	11 " "
Handling at boom (including unloading, sorting, rafting and towing)	9 " "
Stumpage	13 " "

We therefore see the great expense to the logger in felling the trees and gathering them from the woods, and in hauling them to tidewater. It is in connection with these two items that electricity has its greatest possibilities.

There has been developed, for the logging engine, a motor which has all of the characteristics demanded, viz., heavy construction; ability to stand severe overloads; ease of control and no complicated parts. After exhaustive tests the Potlatch

Lumber Company put the first two electric logging engines into commercial operation in 1912*. These outfits operate on an overhead system, lifting the logs from the ground and letting them come in practically by their own weight in hillside work, or pulling them in when working in flat country. Typical operating data are given in Mr. Barry's paper.

Motor Equipments

The motor equipments shown in Figs. 1, 2 and 3 are adjustable-speed 150-h.p., 600-rev. per min. synchronous speed, 550-volt, three-phase, 60-cycle induction motors. Power is received at portable transformer substations—one substation for each equipment—at 11,000 volts and is stepped down to 600 volts for use at the motors. See Fig. 4. Rubber-covered armored cables run along the ground from the substation to the motor, the distance never exceeding 1000 ft. (304.8 m.).

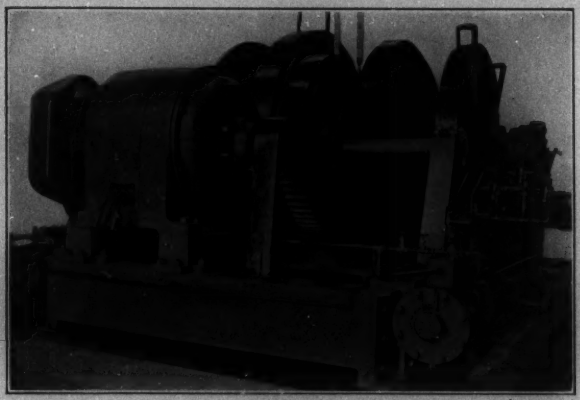
In order to prevent mechanically over-taxing the equipments, an inverse-time-limit overload oil switch is set to give practically instantaneous operation when the pull upon the main cable reaches its breaking strain. For quickly starting or stopping and to prevent overwinding the cable, a solenoid brake is mounted on the front end motor shaft extension.

These outfits are also called upon to load the logs on cars and to spot the cars, and even under these conditions the electrically operated outfits hold the camp record for a day's operation, viz., 55,000 ft. board measure, gathered and loaded by one logging machine in one day. This quantity is comparative only to this company's other operations; the capacity of steam donkeys under similar circumstances is 40,000 ft. per day.

The following table gives representative performance figures for the various operations:

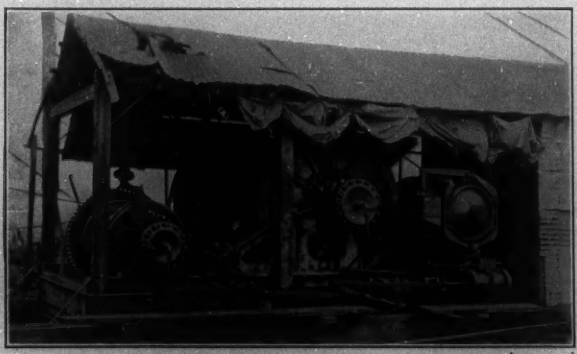
Work Performed	Input	Duration.
Tightening standing line, 2800 ft. of 1¼-in. steel cable	260 kw.	10 sec.
Running trolley out	Accelerating, 100 kw.	
	Running free, 35 kw.	40 to 60 sec.
Pulling trolley in with logs;		
1 log, 800 ft. b. m.	70 kw.	40 sec.
4 logs total 2000 ft. b. m.	145 "	65 "
3 " " 1600 ft. b. m.	210 "	60 "
1 log " 1100 ft. b. m.	85 "	70 "
1 " " 1800 ft. b. m.	95 "	90 "
Loading logs on cars	max. 100 "	
	min. 70 "	3 to 5 sec.
	avg. 85 "	
Moving cars	max. 225 "	
	min. 25 "	3 to 5 sec.

*E. J. Barry—A.I.E.E. Proceedings, September, 1913.



[WHITNEY]

FIG. 1—FRONT END, ELECTRIC LOGGING ENGINE



[WHITNEY]

FIG. 2—ELECTRIC LOGGING OUTFIT MOUNTED ON SKIDS AT SCENE OF OPERATION

FIG. 3—FIRST TRIAL OUTFIT, USING STANDARD MOTOR EQUIPMENT
This outfit operated successfully under varying conditions for a period of three months, to obtain data for later applications.

FIG. 4—PORTABLE TRANSFORMER SUBSTATION, 11,000 TO 600 VOLTS. ARMORED CABLE LEADING TO LOGGING ENGINE AT LEFT

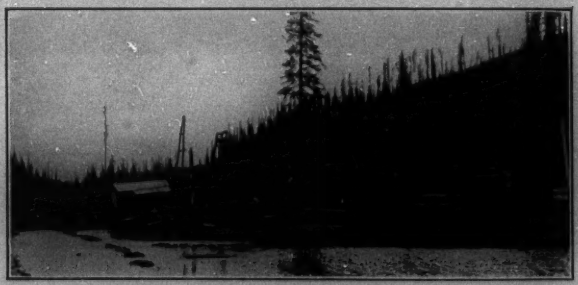


FIG. 5—GENERAL VIEW OF POTLATCH LOGGING OPERATION. ELECTRIC LOGGING ENGINE AT LEFT, SUBSTATION AT RIGHT. [WHITNEY]

In all of the above operations the load is of short duration, so that the daily energy consumption is small. For a 10-hr. day approximately 400 kw-hr. are consumed gathering and loading 50,000 ft. b. m. Fig. 5 shows a typical logging scene in this country. Fig. 6 shows the type of equipment adopted by the C. A. Smith Lumber & Mfg. Co. It is intended for hauling logs on the ground by the old method of "skidding". The motor is wound for 2200 volts. This pressure has been adopted by this company as most economical under its conditions, which require that it cover at least one mile in every direction from a distributing point, to several operating locations. A permanent 60,000/11,000-volt substation in the center of its holdings will distribute to three or four 750-kw., 11,000/2200-volt portable substations, each feeding one unit of its operations.

Of late, a great deal of attention has been given to the use of oil fuel and coal, as well as wood, for logging engines, and in order to see the comparative operating costs the following figures, covering fuel and labor for a logging engine only, have been prepared. These figures are based upon operations under similar conditions in the same camp and doing the same general work.

Average quantity handled per day	76,200 ft. b. m.*
" distance of yarding	670 " (204.2 m.)
" size log	1900 " b. m.*
" time per log	15 min.
" wood burned per day	1650 ft. b. m.*
" fuel oil per day	†8.8 bbl. (11,192 liters)
" coal per day	2½ tons (2.245 metric tons)
Electric power energy consumption	475 kilowatt-hours

Outfit working 70 per cent of time—delays 30 per cent of time.

*In *lumber scale* 1 ft. b. m. is the equivalent of a board 12 in. (30.48 cm.) long, 12 in. (30.48 cm.) wide and 1 in. (2.54 cm.) thick, or 144 cu. in. (2359.7 cu. cm.). The *log scale* considers all items of loss in manufacture and endeavors to allow for these losses so that the log estimate and lumber production may approximately agree. It considers loss due to saw kerf, defects in log, varying diameters at top and butt, etc. There are several rules used in different localities—one will under-estimate the lumber in small logs—another will under-estimate large logs—and the third (which is rather generally used on the Coast) gives a mean value, approximating more closely conditions as found. The above values refer to log scale and therefore represent a greater cubical content than would be the case after same was manufactured into lumber. A very good comparison is given by the following:

1000 ft. b.m. log scale weighs approx. . . . . 8000 lb. (3628.8 kg.)
1000 " " lumber scale (green lumber) . . . 3300 " approx. (1497 kg.)

† 1 bbl. oil = 336 lb. (152.4 kg.)

Electric Operation:	
475 kw-hr. at 1½c. per kw-hr.	$ 7.13
One motorman	3.75
Total per day	$10.88
Oil Operation:	
†8.8 bbl. at $1.15 per bbl.	$10.12
Engineer	3.75
Water—(based on ½ of pumping engineer's time and ½ fuel consumption for pumping engine)	2.67
Total per day	$16.54
Coal Operation:	
2½ tons at $4.25	$10.62
Engineer	3.75
Water (see Oil Operation)	2.76
Total	$17.13 (per day)
Wood Operation	
1650 ft. b. m. at $7.00 per M	$11.55
Engineer	3.75
One wood bucket	2.75
Water (see above)	2.88
Total per day	$20.93

The fuel costs given above are arbitrary and are taken as general averages. It is questionable whether oil and coal can be delivered to the donkeys for such a low price, considering all items—handling, storing, pumping, etc. Without doubt, the cost of fuel would be higher than the value assumed, in the majority of operations. The cost of wood for fuel is estimated as follows:

Stump value	$2.50 per M.
Logging cost	4.00 " "
Extra cost for placing behind donkey	0.50 " "
Total	$7.00 per M ft. b.m.

The higher interest charge in the case of electric operation due to first cost of transmission line, substation, etc., is more than offset by the very much greater depreciation in the case of steam-operated outfits. No attempt has been made to cover this item for all cases. As a conservative estimate, however, the maintenance of a logging engine boiler 72 in. diameter by 144½ in. long, with 374 two-in. tubes, is not less than $200.00 per year, and in view of the severe service its useful life will nbt exceed eight to ten years.

Averaging the above costs for fuel and labor, with oil, wood and coal, shows a net saving of $7.35 per donkey per day in favor of electric operation.

An electric unloader is used which dumps the logs from the

cars at tidewater. This is operated by a 37-h.p. hoist motor, and unloads 30 cars, each containing 7000 ft. b.m., in approximately 20 minutes. This time includes that necessary for spotting the cars at the log dump. This unloader used a total of 90 kw-hr. for unloading 4000 M. ft.

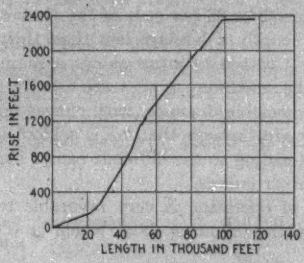


FIG. 7—PROFILE OF LOGGING ROAD NO. 1

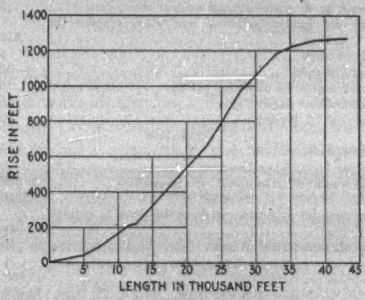


FIG. 8—PROFILE OF LOGGING ROAD NO. 2

LOGGING RAILWAYS

Figs. 7 and 8 show typical condensed profiles of two logging railways. Usually the country to be tapped is rugged and mountainous, necessitating heavy grades and sharp curves. Track construction is as light as possible. As a general rule the grade is in favor of the load and in most cases very little energy is required on the down or loaded trip. Oil is the common fuel. Because of the grades encountered slow speed locomotives find

a wide use, the slow schedule speed requiring train operation almost continuously during working hours. The lengths of these roads are usually very favorable to electric operation, allowing a round trip to be made in a reasonable time and not necessitating a train of excessive length.

In only three of the thirteen counties in Washington and Oregon which produce 88 per cent of the timber in these states is the average length of haulage less than thirteen miles. An average of the thirteen counties shows a main line length of 15.2 miles. The maximum grades are usually from 5 to 7 per cent for an appreciable distance, with curves up to 20 degrees. The average grade through the line is seldom less than 2½ per cent and spurs leading to the different camps have even heavier grades and sharper curves.

An analysis of operation is very favorable to electricity, as will be seen by the following data, which give conditions of a typical road:

General Data:

Length of line	21½ miles.
Average grade with load and against empty cars	2 per cent
Maximum grade, including equivalent friction for curves	5.5 per cent.
Gage of track	4 ft. 8½ in.
Weight of rails	60 lb.
Loaded cars to be delivered per day	75
Weight of car empty	18½ tons.
" " " loaded	50 tons.
OPERATION	
Weight of locomotive	60 tons.
Cars per train either direction	9
Total weight of train uphill, one locomotive	226½ tons
" " " " downhill "	510 tons.
Total time for round trip without layovers or switching	144 minutes.
Schedule time for round trip	3 hr.
Round trips per locomotive per day	4
Ton-miles per round trip	15,800
" " " day—8 round trips	126,400
" " switching	6,500
Kilowatt-hours per day at locomotive	6,110 kw-hr.
" " " " from high-tension bus	9,050 kw-hr.
Ave. load per day of 12 hrs. from transmission system	754 kw.

Three locomotives are required for this service, two main line and one for switching.

With 1200-volt electrification, two 500-kw. substations will care for the power demand. The total approximate cost of the locomotives, substations, transmission line, overhead, bonding and feeders is $190,000.00.

For similar operation with oil-burning locomotives, two 125-

ton standard slow speed freight locomotives and four 50-ton geared type locomotives are required, and even with this equipment the train must be broken at the heaviest grade, necessitating a return trip for a portion of the empty train which starts from the terminal.

The locomotives burn oil fuel, which costs approximately $1.15 per barrel for main line locomotives and $1.20 per barrel for switching locomotives at the logging camps. Electric power can be purchased for 0.9 cent per kilowatt-hour net.

The following table of maintenance and operation, omitting those items which are approximately the same under the two conditions, shows a net saving of $20,068.00 per year with the electric railway:

	ELECTRIC	STEAM
Interest and depreciation	$19,000	$ 9,200
Maintenance	7,168	10,436
Wages	10,200	21,300
Power or fuel	24,500	38,500
Supplies	1,500	3,000
Total	$62,368	$82,436

Under "electric operation" the different charges cover both substation and train operation. There are some items which ordinarily would favor electric operation—for instance, track maintenance has been considered the same in both cases and omitted from our consideration, since in logging railway operations the greatest damage to the tracks appears to come from the swaying of the loaded cars, and not from the locomotives.

With steam operation, 84½ bbl. of oil were used per day for main line haulage for the two 125-ton freight locomotives, and two 50-ton shays, and 22.3 bbl. per day for the two 50-ton switching locomotives. In this present instance the steam locomotives are taxed to their utmost capacity while logging operations are being carried on at the near end of the timber holdings.

It will be necessary within a few years for this road to be extended approximately twelve miles further, the prevailing grade on the extended line being the same as at present, and an analysis of the future conditions will show that four locomotives operating thirteen hours each per day will be able to care for the output and the conditions will then be very much more favorable for electric operation.

Milling

Under the first heading will come all that part of the manufacturing plant which converts the logs into timbers or boards, including all operations—from taking the log from the pond until the rough manufactured product is sorted into its various dimensions and lengths, ready for storage or further manufacturing. These operations may be divided into the following branches: handling the logs: sawing: trimming and sizing: disposing of refuse: sorting: storing or shipping.

In order that the sawmill operator may more profitably dispose of his better grade stock, a finishing mill is a necessity and in reality such a more or less completely equipped mill is always understood to be included in the general term "sawmill". The operations are so distinct, however, that it has been thought best to include the planing mill under a separate heading.

In those mills which finish a large portion of their product, there is between the sawmill and planing mill a seasoning process, which we will term "treating". This consists of artificially drying the product before finishing it. Its object is to get the material to its ultimate seasoned dimensions before the final manufacturing operation. Those operators who must overcome the handicap of high freight rates secure an additional advantage in eliminating all excess weight due to moisture. Some specialty mills (shingle mills, for instance) resort to drying solely for the purpose of reducing weight.

The treating process includes: stacking: drying: unstacking: sorting.

For economy of space, the material must be stacked in some uniform manner; industrial type flat cars are generally employed, with mechanical means for loading the lumber upon these cars. With the old method of hand stacking, the capacity of two men per day seldom exceeded 10,000 ft. b.m., which is approximately 2000 boards.

When the electrically operated stacker is used, the boards are taken directly from the sorting chain and two men can care for from 45,000 to 50,000 ft. per day. The lifting arm of this equipment, which lifts each stack in position, together with a short section of the conveyer table, is operated by a 7½-h.p. motor, belted to a line shaft and running continuously. The load factor is not more than 5 per cent. The peak when lifting the arm is approximately 12 h.p., while running the mechanism light requires 2 h.p.

The dry kilns universally follow the old principle of steam radiator construction. The steam legs of the radiator are made up of a large number of small pipes, one in. (2.54 cm.) to 1½ in. (3.81 cm.) in diameter, which run the length of the kiln and connect to steam exhaust headers at the end. A typical dry kiln layout is shown in Fig. 9. It is common practise to admit high-pressure steam directly to the pipe. Of late years the vacuum system, taking exhaust from the mill engines at 5 to 30 lb. (2.2 to 13.6 kg.) gage and exhausting into 20 to 25-in. (50.8-to 63.5-cm.) vacuum, has come into rather general use. Where high-pressure steam is used directly, a reducing valve which cuts the pressure to approximately 50 lb. gage is ordinarily inserted.

It requires about 72 hours for drying planing mill stock, and six days for drying bundles of shingles. After the kiln has once reached a constant temperature approximately 1000 lb. (453.5 kg.) of steam per hour are required by the average kiln.

In green lumber, 30 per cent to 40 per cent of the weight is moisture. The dry-kiln operation reduces this to from 6 per cent to 10 per cent after drying. The process is not carried further as there is no necessity of furnishing lumber drier than the air at the locality in which it is to be used.

After drying, the lumber is unstacked and distributed to the finishing machines. The scheme for unstacking edge-piled lumber in most common use consists of an endless chain with hooks spaced about 10 ft. apart, running in vertical guides, these guides at the top being curved to direct the boards on to a conveying table. As the hooks revolve, they engage the bottom of the stack, lifting it from the car, and the top guides direct to a transfer table, from which it goes to the sorting table and is classified and taken to the finishing machines. This unstacking device is driven by a 5-h.p. constant-speed motor and requires approximately 4 h.p. while lifting the stack and 1¾ h.p. running the lifting and conveying chains only. Its unloading capacity is approximately 60,000 ft. b.m. per day.

Planing Mill

Operations in this mill consist of planing or finishing the stock, trimming, disposing of refuse, sorting, tying or bundling and storing or shipping.

The product of this mill comprises the highest grade lumber and is consequently given close attention.

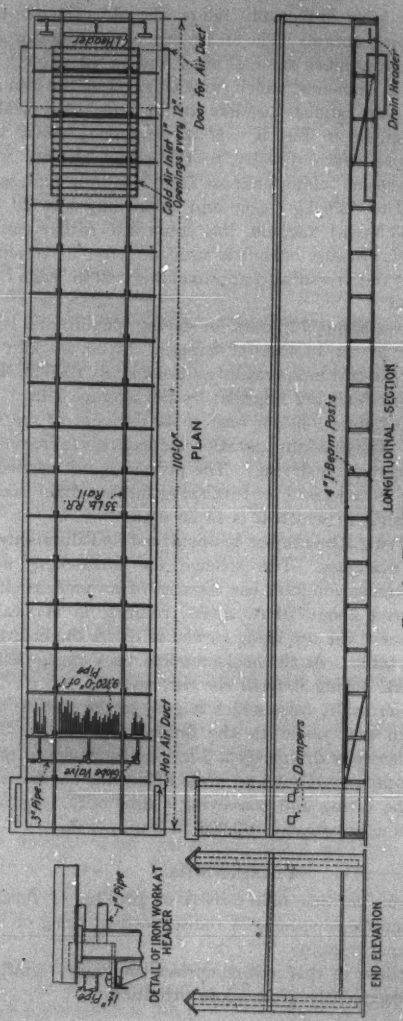


FIG. 9—DRY KILN LAYOUT

Before planing, it is often necessary to do a small amount of re-saw work, but this is of a very light character, its purpose being to re-manufacture yard stock to supply the accumulation of orders for any one size of lumber. The refuse from this mill is the best fuel supply, since it is thoroughly dry.

Specialty Mills

Specialty mills are often valuable adjuncts in utilizing materials which would otherwise be thrown away as refuse. Very often they have no connection whatever with sawmills and must purchase their material in the open market. In the following, therefore, we have considered only those specialty mills which have a direct connection with sawmills.

Lath Mills

Lath mills are always run in connection with sawmills and obtain their material from slabs and edgings which would otherwise go to the refuse burner or, at best, to the wood bins. The slabs are taken from the main refuse conveyer and go through the following processes: bolter: lath machine: trimming, bundling.

Bolting consists of sizing the slab to the dimensions necessary for putting through the lath mill. The bolter may consist of a number of saws, therefore making several bolts at one operation, and requires about 7½ h. p. per saw.

The lath mill consists of three saws, making four laths of each bolt, and requires approximately 25 h. p. The laths are then trimmed to 4-ft. (1.21-m.) lengths and tied in bundles of 50 or 100, after which they are ready for storage or shipment.

Saw Mills

In saw mill operations the work consists essentially in manufacturing a log to boards or timbers of a certain thickness, width and length, so in its elementary form only three machines to perform these functions are necessary. In the following, therefore, we will follow the progress of the work through the mill in its simplest form, afterwards returning to the auxiliary machines which have come as a natural result to increase production by performing some of the elementary functions faster or with greater facility than could be done with only the major machines.

In driving the mill machinery, squirrel cage motors are used

wherever possible, because of their simplicity and strength. Unless specifically noted to the contrary, it will be understood that constant-speed, alternating-current induction motors are referred to. Practically all of the work is at constant speed, and in fact in sawing operations this is of prime importance. In the first installations, individual drive for each device or machine was used without question, thus, at one step, past practise with line shaft and belting, with all group drives, was entirely reversed, in an endeavor to do away with shafts, belts and transmission machinery entirely. Today, semi-group drive is standard. All parts which work to the same end and are close together, are grouped. Groups usually embrace such devices as transfer rolls, transfer chains, conveyers, etc., which require a certain amount of transmission machinery in any event, and which require practically the same power when running idle as when working. The milling machines themselves are individually driven.

The power demands of the machines fluctuate so that it is practically impossible to plan for other than the maximum demand which might be encountered. For instance, an edger may run on narrow material with two saws cutting a two-in. board, and within five minutes, the same machinery may be called upon to handle a 6-in. (15.24-cm.) to 12-in. (30.48-cm.) cant, requiring four or five working saws, taking in the first place approximately 40 h. p. and in the second place 350 h. p.

In the following, wherever load factor is given, it is taken as load factor based upon the time of a working day. Some mills operate 24 hours, while others run 10 hours, and it is therefore obvious that unless the actual working time for each day is taken, the data will not apply universally.

Fig. 10 gives the general plant and yard scheme of a modern Pacific Coast mill. The logs as delivered to the pond are of various lengths and sometimes must be cut to accomodate the mill layout. This operation is performed more often when the logs are still in the water, but is sometimes done after they have been lifted to the log deck. Fig. 11 shows the saw used in the latter way. The driving motor is a squirrel cage type, 10 h. p., and is run intermittently. Its load factor is not greater than 6 to 7 per cent.

Log Lift

The logs are carried from the pond either by the old arched log haul, or by the later log lift (Fig. 12). In the first case an endless

[WHITNEY]

FIG. 6—LOGGING ENGINE OF C. A. SMITH LUMBER AND MANUFACTURING COMPANY AT MARSHFIELD, OREGON

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FIG. 11—LOG SAW ON LOG DECK IN MILL. CONTROL FOR LOG HAUL AND CONVEYER CHAINS SHOWN AT RIGHT

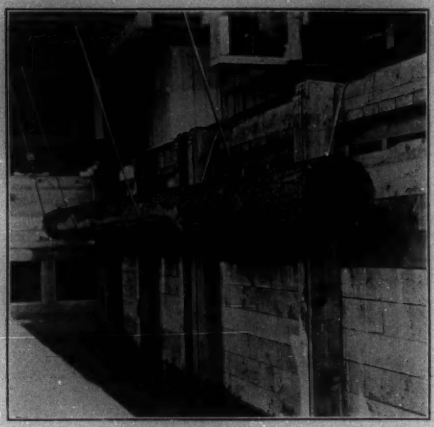

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FIG. 12—LOG LIFT WITH LOG AT HALF ELEVATION

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FIG. 15—TEN-FOOT BAND HEADSAW AND LOG CARRIAGE AT END OF TRAVEL. BOARD WHICH HAS JUST BEEN CUT IS LYING ON LIVE ROLLS

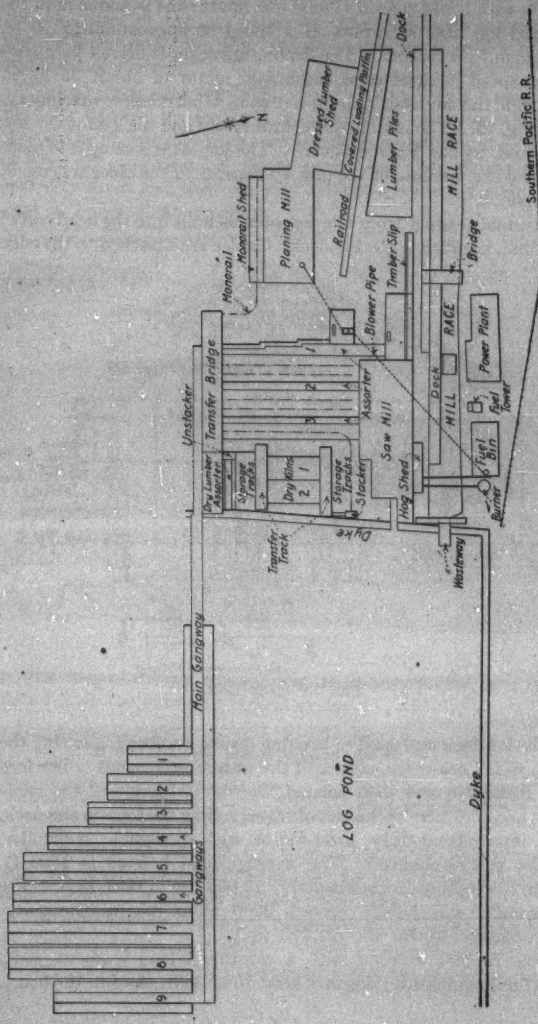

FIG. 10—YARD LAYOUT—BOOTH-KELLY LUMBER COMPANY

chain with hooks spaced several feet apart runs in a groove in the arched log haul structure, at a speed of approximately 50 ft. (15.25 m.) per minute. The driving sprocket is driven by a constant-speed squirrel cage induction motor of about 35 h. p., through the necessary speed-reducing transmission machinery. See Fig. 13. The motor runs continuously and the load is thrown on or off by the friction device. The log lift is coming into more general use, because of the upkeep expense of the older scheme of log haul.

A canal leading from the log pond is built into the head end of the mill, paralleling the log deck. Cables are attached to the edge

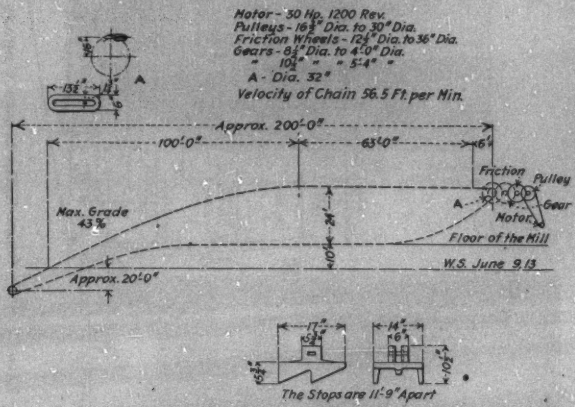

FIG. 13—LOG HAUL

of the log deck and fixed to hoisting drums overhead, allowing the loop to fall below the surface of the water in the canal. The logs are floated in and then hoisted, the natural angle of the cable as it becomes taut at the end of travel rolling the logs on the deck. An intermittent-duty hoist-motor, with reversible controller, drives the mechanism. The average load hoisted is 1500 ft. b. m., weighing approximately 12,000 lb. (5443 kg.). The maximum will hardly exceed 6000 ft. b. m., weighing approximately 48,000 lb. (21,772 kg.).

The rate of hoisting with a maximum load is about 40 ft. (12.1 m.) per minute; length of hoist 10 to 35 ft. (3.05 to 10.76 m.).

Common practise requires 37 to 52 h. p., depending upon the character of the logs handled. The load factor is approximately 6 per cent. See Fig. 14, showing a cross-section of the head end of a sawmill at the head saw.

The adjuncts of a log deck, viz.: "kickers" and "niggers," used for turning the logs and pushing them on the carriage, as well as the log carriage itself, are usually steam-operated. These devices are uneconomical steam users, but their demands are not very great and they are very seldom a source of additional cost in boiler plant capacity.

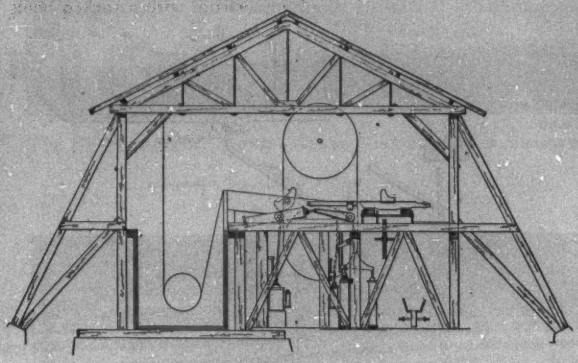

FIG. 14—SECTION AT HEADSAW

The duty of the log carriage, Fig. 15, is very severe, as may be noted from the following typical cycle:

Average speed during cut	250 ft. per min.	(86.25 m.)
" " of return (assuming single cutting mill)	650 " " "	(198.25 m.)
Total distance of travel one direction	20 to 60 ft.	(6.1 to 18.3 m.)
Average weight of carriage and log of 1500 ft. b. m.	38,000 lb.	(17,237 kg.)
Maximum speed during cut	350 ft. per min.	(106.75 m.)
Minimum speed during cut	100 ft. " "	(30.5 m.)

From these we see that the retardation at the end of travel and the acceleration of return must be at very high rates in order to lose a minimum of productive time.

The log after each cut must be moved up a definite amount in preparation for the next cycle. This is accomplished by the set works. A five-h. p. constant-speed induction motor mounted

on the carriage and running continuously provides the simplest means of driving this device.

With direct current available, a series motor will prove more economical in energy consumption and will run only when the set works is operating. Current is collected from protected trolleys or from a loop cable supported by rings carried on a rod attached to the side of the building. A back-geared motor or one fitted with silent chain drive proves most compact. The control mechanism must be arranged for reversing operation.

The canting gear, usually driven by a 15-h.p., constant-speed motor, is required only when a very irregularly shaped log is encountered. It consists simply of a drum with attached hook

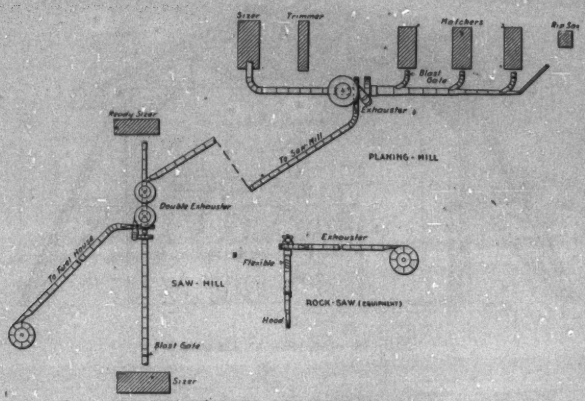

FIG. 16—REFUSE EXHAUST SYSTEM

and cable for turning the log on the carriage. This operation is now performed by power machinery in all except the most extreme cases. The motor operates so intermittently that its energy and power requirements are of little interest.

ROCK SAW

A small saw ordinarily known as a "rock" or "barking" saw, to remove gravel, barnacles or other foreign matter from the bark of the log, usually precedes the main saw in the line of cut. It operates continuously, and requires a 15-h.p. motor; its load factor is approximately 30 per cent. A tin housing, piped to an exhaust fan, allows the dust to be carried away. This fan

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FIG. 17—MILL FLOOR, SHOWING THREE NINE-FOOT BAND HEADSAWS

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FIG. 18—300-H. P. MOTOR DRIVING 10-FT. BAND SAW IN PACIFIC COAST MILL

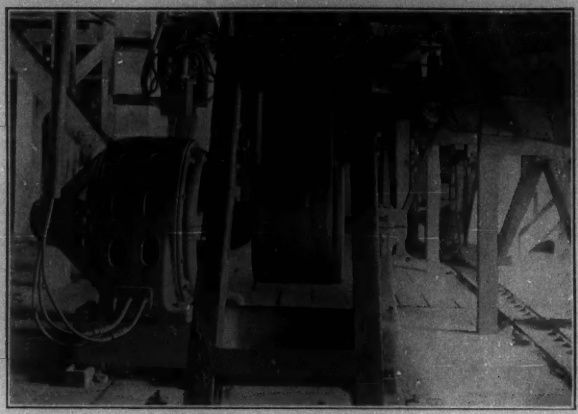

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FIG. 19—250-H. P. SQUIRREL CAGE MOTOR DRIVING DOUBLE 66-IN. CIRCULAR HEADSAW IN PACIFIC COAST MILL

[WHITNEY]

FIG. 20—TYPICAL GROUP FOR DRIVING TRANSFERS, LIVE ROLLS, ETC.

requires 15 h.p. and runs continuously at constant speed, with a load factor of approximately 100 per cent. See Fig. 16.

Head Saw

The essential duty of this saw is to cut timbers of a certain thickness from the log. Refinements of this process—*i.e.*, reducing these timbers to boards—really fall to other machines, viz., re-saws and gang saws, because of operating requirements. The single-cutting band mill is by far the most popular type of head saw; double-cutting mills are in general use when handling smaller timbers than are common in the Pacific Coast country, but circular head saws are by no means obsolete.

A typical 10-ft. (3.05-m.) single-cutting band mill is shown in Figs. 15 and 17. Driving this is a 300-h.p. constant-speed motor with wound rotor, and provided with drum controller and resistance for starting duty only. The large inertia of the heavy saw tension and driving wheels imposes severe starting conditions, but once up to speed, helps greatly in equalizing the load, so that in running we seldom encounter very high peak demands. The following data are typical of a mill of this capacity:

Speed of saw wheels	300 rev. per. min.
Running demand range	230 to 450 kw. input
Starting demand	560 kw. input
Duration of starting demand	38 seconds
Running light, input	60 to 70 kw.
Average kw-hr. per day of 10 hr.	1050
Load factor—average*	22 per cent

Because of the slow speed of large band mills the motor is usually belted and a belt tightener used. See Fig. 18. Three-bearing motors are universal practise.

The polar wound-rotor type for constant speed service is commonly used, to limit the current input at starting. Where ample station capacity is available a squirrel cage motor can be used with impunity, now that the electrically-welded rotor end-ring construction has so greatly increased its ability to withstand long-sustained starting periods without damage. The simplicity and strength of a squirrel cage type motor makes its use very desirable.

With double-cutting mills the load factor and daily kilowatt-hour consumption are higher than the values given above. The power per thousand feet, however, is lower, due to the greater proportion of working to idle periods.

*In this instance, as in the others cited, the load factor may not agree exactly with the performance figures given—all figures are averages of a large number of tests and are indicative of average performances only.

Circular Head Saws

Squirrel cage motors are universally used for circular head saws. The inertia of the circular saws is low and the load fluctuations during the cut must be taken care of entirely by the motor. Fig. 19 shows a motor driving a double circular 66-in. (1.68-m.) saw. Where the saw speed permits, the best practise is to connect the motor directly to the lower saw arbor, driving the top saw with a belt. The following operating data are typical of a large double circular head saw:

Running demand range	240 kw. to 560 kw. input
Starting demand	360 kw. input
Duration of starting period	15 seconds
Running light	35 kw.
Average kw-hr. per day of 10 hr.	1150
Load factor, average	20 per cent

From the head saw, the boards or cants are conveyed by rolls and transfer chains which distribute the product to the other machines (Fig. 20). The rolls directly in front of the head saw run at speeds of about 350 ft. (106.7 m.) per minute, the speeds in later sections decreasing slightly.

Present practise leans toward grouping two sections of roll with one or more sets of transfer chain, driving the group from a countershaft operating at 900 rev. per min., and driven by a direct-connected, constant-speed, squirrel cage motor. All rolls must be arranged for both forward and reverse operation, and the simplest scheme for accomplishing this and at the same time relieving the motor of all starting demands, requires the use of friction devices.

With individual motor drive, a back-geared reversing motor with chain drive from the back-geared shaft provides the most compact arrangement. Such a motor should preferably be of the polar-wound rotor type. Fig. 21 shows a general scheme using group drives.

Live rolls 12 in. (30.48 cm.) diameter by 30 in. (76.2 cm.) long require approximately 0.4 h.p. per roll when operating at 200 rev. per min. When operating at 100 rev. per min. they require approximately $\frac{1}{4}$ h.p. per roll. As a typical group, a section containing eighteen 12-in. by 30-in. (30.48 by 76.2-cm.) rolls at 120 rev. per min. and thirteen 12-in. by 30-in. (30.48 by 76.2-cm.) rolls at 80 rev. per min., three slab transfer chains, and three edger transfer chains, requires seven kw. input.

As an example of individual motor drive, with back-geared motor and chain drive to one roll case containing fifteen 12-in.

by 32-in. (30.48 by 76.2-cm.) rolls driven from a line shaft by bevel gearing, the maximum running load is 4.8 kw. and the average running load is 3.7 kw. This information applies to cases where rolls are well lubricated and gearing in first-class shape. No average conditions can apply generally, since by far the greater part of the load is due to friction.

Edger

The function of this machine is to cut the stock to width after it has been cut to a predetermined thickness by the head

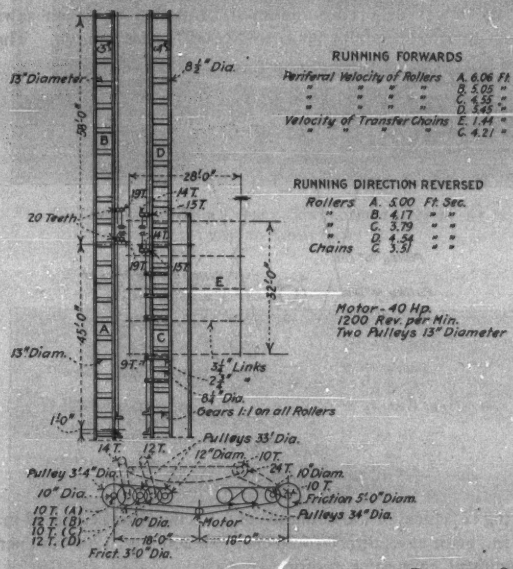

Fig. 21—Grouping of Live Rolls and Chains Driven by One Motor

saw. It therefore consists of a number of circular rip saws, with the position of each adjustable on an arbor, the total width of stock determining the number of saws working at any one time and their position. See Fig. 22. Edgers adapt themselves admirably to direct connection; their speed is high and saw sizes can be so chosen as nicely to fit a 1200- or 1800-rev. per min. motor, which speeds are suitable for direct connection.

The starting load is comparatively light; the running load fluctuates through wide ranges and the saw speed should be practically constant, which conditions have caused the squirrel cage, constant-speed induction motor to be universally adopted. The feed rolls should be reversible, and capable of having their speed adjusted (see Fig. 23), the rate of feed depending upon the stock and varying from 325 ft. (99.1 m.) per minute to 120 ft. (36.6 m.) per min. For driving these rolls the latest practise has adopted a varying-speed, constant duty, reversing motor with polar-wound rotor.

On the edger arbor are mounted from five to seven saws running at rim speeds of 9000 to 12,000 ft. per minute. The

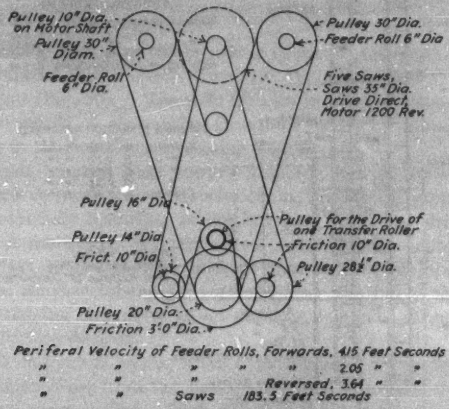

FIG. 23—FEEDER ROLL DRIVE

following is typical of the demands of a Pacific Coast edger 12 in. by 72 in., eight saws direct-connected to a 200-h. p. 1200-rev. per min. squirrel cage type motor:

Input—idle	35 kw.
—5 saws cutting 6 in. stock @ 220 ft. per min.	350 "
—5 saws cutting 6 in. stock @ 135 ft. per min.	247 "
—3 saws cutting 10 in. stock @ 135 ft. per min.	290 "
—4 saws cutting 2 in. stock @ 230 ft. per min.	75 "
—6 saws cutting 1½ in. stock @ 240 ft. per min.	75 "
Average per 10 hr. day	405 kw-hr.
" load factor	11.6 per cent.

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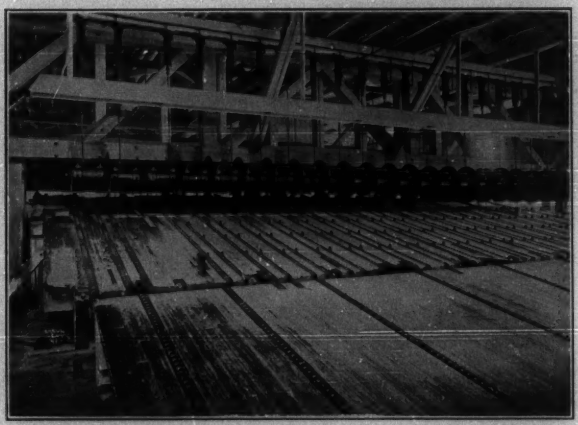
FIG. 22—200-H. P. MOTOR DIRECT-CONNECTED TO 12½ BY 84 IN. EDGER HAVING EIGHT SAWS



[WHITNEY]

FIG. 25—FRONT OF 40-FT. TRIMMER REQUIRING A 50-H. P. MOTOR

[WHITNEY]

FIG. 27—TRANSMISSION FOR SORTING TABLE. DRIVE RATIO 900 TO 1

FIG. 28—BAND RE-SAW WITH DIRECT-CONNECTED MOTOR [WHITNEY]

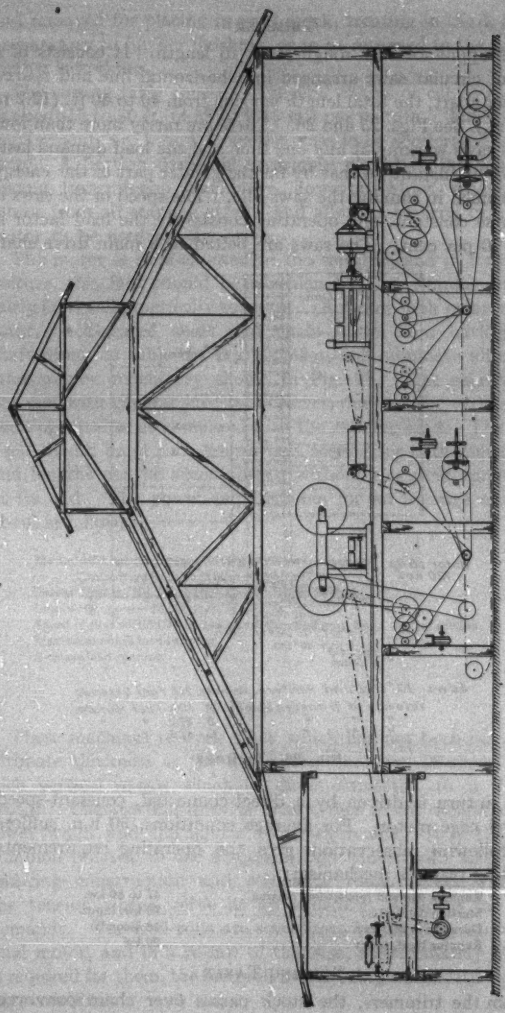


FIG. 24—SECTION AT EDGER AND RE-SAW

Trimmer

This appliance cuts rough stock to length. It consists of a gang of circular saws arranged in a horizontal line and spaced two feet apart, the total length varying from 40 to 50 ft. (12.2 to 15.25 m.). See Figs. 25 and 26. There are rarely more than four or five saws working at any one time and the load demand lasts only for an instant, so that by far the greater part of the energy is consumed in running the saws idle. The speed of the saws is of course constant, and operating constantly the load factor is 60 to 70 per cent. The saws are belted to a main drive shaft

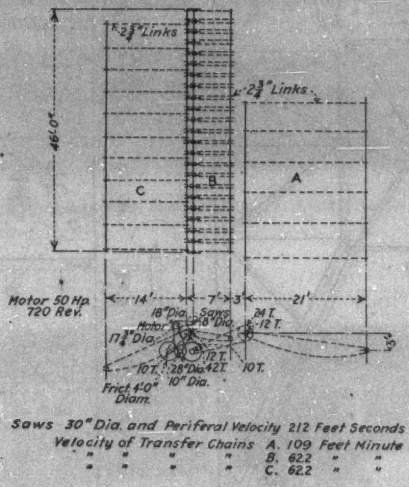


Fig. 26—Trimmer

which in turn is driven by a direct-connected, constant-speed squirrel cage motor. For average conditions, 50 h.p. suffices. The following observations give the operating requirements including transfer mechanism:

Running demand range when cutting	47 to 80 kw.
Starting demand	70 kw. input.
Duration of starting	18 seconds
Running light, input	29 kw.

Sorting Table

From the trimmers, the stock passes over chain conveyers spaced 4 ft. (1.22 m.) apart, to the sorting table, where it is graded

and removed for placing in yard stock, treating in the dry kilns preparatory to further finishing, or to be returned to the mill for further reworking.

The sorting table consists of several chains or cables running at about 15 to 30 ft. (4.58 to 9.15 m.) per minute. The starting requirements are heavy, since the mass to be accelerated is very large. A friction device is invariably placed in the speed-reducing transmission machinery, however, which relieves the motor from all starting strains and allows a squirrel cage type motor to be used for the drive.

The motor is semi-exposed to the weather, and in its manufacture, this fact should be considered. The running load is fairly light and practically constant. A motor with polar-wound rotor, back-geared shaft and chain drive from back-geared shaft direct to table driving sprocket, will eliminate all of the transmission machinery shown in Fig. 27. This scheme has not met with general success, however, due to the very severe starting strains as compared with the running load. The table itself should be of such length that sorting for both dimensions and lengths can be accomplished without too great congestion at its end. The power requirements for an average case are about as follows:

Motor, 10 h. p. back-geared 850 to 128 rev. per min.
Chain drive from back-geared shaft.
Drives 1596 ft. No. 75 chain—Chain weight 3445 lb.
Lumber per hour—12,000 ft. b. m.
Speed of first section 35 ft. per min.—decreasing to 29 ft. on last section.
Maximum noted load running.....7.5 kw.
Average load running.....5 "

Re-Saws

These machines re-work stock which has not been cut to its ultimate thickness at the first operation. Fig. 28 shows a six-inch vertical re-saw which is direct-connected to a 75-h.p. motor. The starting duty is heavy, due to the weight of the lower wheel and the inertia to be overcome. It is therefore common practise to use a squirrel cage motor with substantial end-ring construction and resistance rotor. When running, the tension wheels serve as an equalizer, reducing the peak demands. The feed rolls are sometimes operated by an individual motor, and in a re-saw of this size, approximately 10 h.p. is required for them, the feed roll motor being a standard squirrel cage machine.

The following are typical service data of a heavy-duty band re-saw:

Rate of feed	185 ft. (56.4 m.) per min.
Splitting, 2 in. (5.08-cm.) by 12 in. (30.48 cm.)	80 kw. input
4 in. (10.16 cm) by 10 in. (25.4-cm)	60 " "
Running light	16 " "

Horizontal re-saws are becoming more popular because of the ease with which they may be instantly adjusted to care for stock of different dimensions. Such a machine can, for instance, handle on one side of its adjustable bed a 6 in. by 12 in. cant, re-sawing to 4 in. by 12 in. and 2 in. by 12 in., and on the other side at the same time re-work a 2 in. by 8 in., making two 1 in. by 8 in. boards. The starting duty is about the same as for the vertical type. The running load fluctuates no more widely.

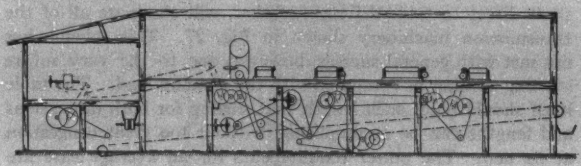


FIG. 31—SECTION OF RIPSAW

GANG SAWS

Gang saws, as the name implies, consist of a number of straight crosscut saws which split a cant at one operation into a great number of boards of the proper thickness. The boards then proceed to the trimmer and are cut to length, as with the output of the edger. These saws have a vertical reciprocating and oscillating motion and the machine is equipped with a flywheel to equalize the load. The average size gang requires a 75-h.p. motor.

A rip saw, Figs. 29 and 30, is required to reduce the width of a certain amount of the mill run, according to order demands. Fig. 31 shows a rip saw, rolls and transfer to rip saw from first section of sorter chains. A silent chain drive or a direct-connected motor may be used. Either method operates satisfactorily, the particular drive adopted depending on the mill layout and space available.

Rough timbers often require no further sizing work than can be performed by the head saw, and never more than an additional passage through the edger. They are conveyed directly to the

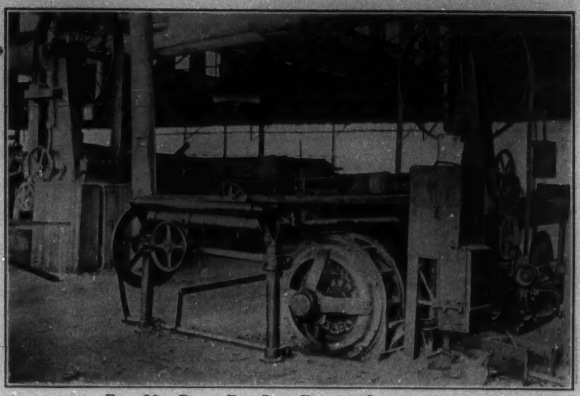
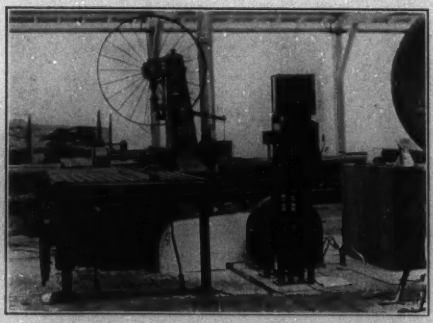


FIG. 29—BAND RIP SAW DIRECT-CONNECTED TO MOTOR. LARGE RE-SAW IN DISTANCE [WHITNEY]



[WHITNEY]

FIG. 30—BAND RIP SAW DRIVEN BY SILENT CHAIN

[WHITNEY]

FIG. 33—BACK-GEARED MOTOR OPERATING CONVEYER

[WHITNEY]

FIG. 34—BACK-GEARED MOTOR BELTED TO BURNER CONVEYER

tail end of the mill, where the ends are squared by a large cross-cut saw—and then proceed to the loading platform. Sometimes, however, for uniformity of alignment in building operations, one or more sides must be planed after the timbers have been squared at the end, and consequently they go to what is known as the "green" mill. This consists of one or more planing machines, with an exhaust fan to dispose of the shavings. The planers ordinarily used for this work are known as "ready sizers," a machine which is quickly adjustable for different size timbers and is arranged to surface only an edge and a side, and "timber sizers," which ordinarily have four cutting heads and can surface all four sides of the stock. The average power requirements of such a machine are as follows:

TIMBER SIZER

Size stock	Feed	Sides sized	Input Kw.
5 in. by 5 in.	60 ft. per min.	4 sides	Avg. 33.2 Max. 41.1 Min. 29.1
2 by 12 in.	125 ft. " "	4 sides	Avg. 46.2 Max 71. Min. 43.

READY SIZER

Size stock	Feed	Sides sized.	Kw. Input
2 in. by 12 in.	96 ft. per min.	side and edge	Avg. 38.2 Max. 50.1 Min. 31.9
2 by 4 in.	96 ft. " "	" " "	Avg. 31.4 Max. 35.6 Min. 26.5

For transferring cants from the main rolls past the head saw to the storage platform in front of the gang saw, an overhead crane transfer is provided (shown at top of Fig. 32). The hoisting and propelling motors are series-wound, direct-current machines, and are supplied from a motor-generator set.

REFUSE

The refuse from the various sawmill manufacturing processes consists of dust from the saws, edgings, trimmings, and shavings from the "green" planers. Figs. 33 and 34 show conveyer drives. V-shaped troughs in which chain and block conveyers run, serve to handle the sawdust from the main mill machines, but from the planing machines the shavings must be carried

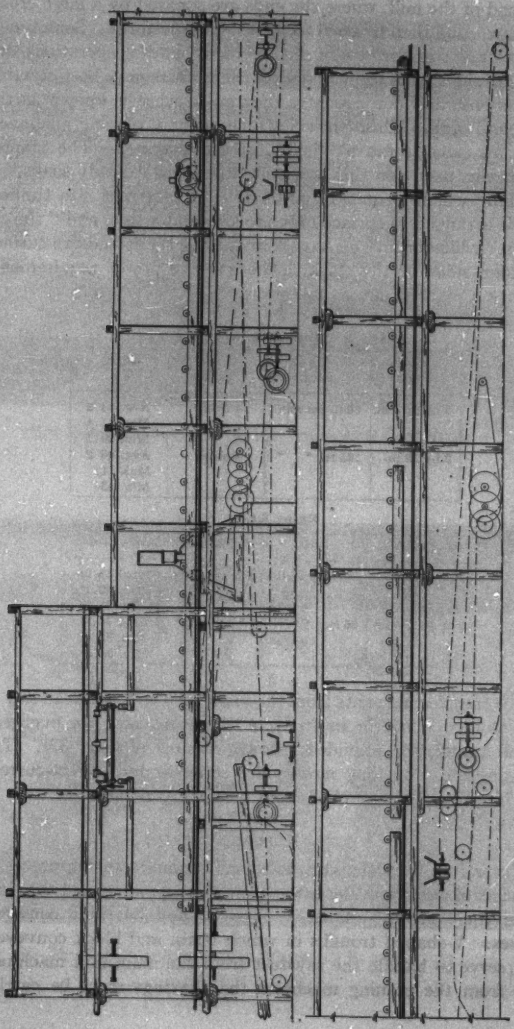


FIG. 32—SIDE ELEVATION OF MILL

away from the knives as fast as possible, so that some pneumatic suction system is necessary.

The edgings are first run through a gang of crosscut saws, a "slasher" with saws spaced 4 ft. (1.22 m.) apart. See Fig. 35. These slabs fall directly into the main mill wood conveyer, which has already received the stub ends from the trimmer which were less than 4 ft. (1.22 m.) long. From this conveyer, Fig. 36, is taken the stock for the lath mill and wood saws. The waste

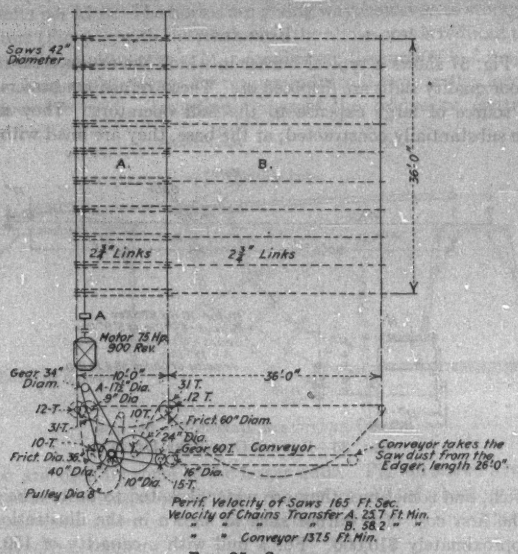


FIG. 35—SLASHER

which is suitable for neither of these purposes, continues to the "hog" and the refuse burner, Fig. 37. The "hog" hashes the refuse into small pieces suitable for use under the boilers, after which it is conveyed to the fuel storage bins. These appliances run at constant speed, and have fluctuating demands.

Dust from the machines is dumped into a main sawdust conveyer, which in turn delivers into the conveyer at the fuel bins. The shavings from the sizers are lifted by suction to a collector and from here blown directly to the fuel bin, Fig. 16.

Piping is usually large, because of the tendency of sawdust, if at all damp, to pack tightly at bends. Low pressures such as can be delivered by centrifugal fans are the rule. The pressure seldom exceeds 5 oz., but the volume is constant and consequently the blowing system is quite extravagant of power. The sawdust and hogfuel from the saw mill, planing mill, etc., if used for generating steam, is more than ample for the total power requirements of the mill. (See table of refuse fuel values at end of paper.)

Burners

Fig. 37 shows a typical burner in which the excess refuse and poor quality slabs are disposed of. These refuse consumers are a source of large expense to the mill operators. They must be substantially constructed; at the base, they are lined with fire

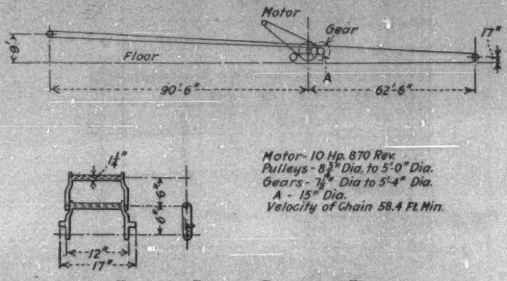


Fig. 36—Refuse Conveyer Drive

brick, and sometimes they are water-jacketed to quite a height. The first cost of a burner such as shown in the illustration is approximately $10,000. For a mill with a capacity of 150,000 ft. b. m. per day, the upkeep expense of such a burner would be approximately $1200 for interest and depreciation, and $1000 for maintenance. The life of an average burner is about 10 years.

Handling

From the sorting table the lumber is placed in bundles ready for handling. The most efficient method where location permits, appears to be by the well-known overhead monorail (Figs. 38, 39 and 40). The cost of handling by this method averages about $.10 to $.14 per M ft. b. m., which includes all expenses in connection with the system after the bundle is picked up until it is

placed in the storage yard or deposited at the dry kiln. This cost covers all charges against the system for labor and operating.

The first cost, installed, of such a system is $4.00 to $5.00 per lineal foot of track, including the hoists, and it provides about 2000 ft. b. m. storage space per foot of track. The monorail is usually operated by direct-current power at 250 volts, requiring a motor-generator set or small direct-current steam-operated set. The cost of handling with trucks and horses is approximately 25 cents per M ft. The horses are giving way, however, to storage tractors (Fig. 41), with the result that the above cost is reduced to approximately 10 cents per M ft. for average distances of handling.

For long hauls, storage battery or industrial type trolley locomotives are used. Traveling cranes of the bridge or gantry

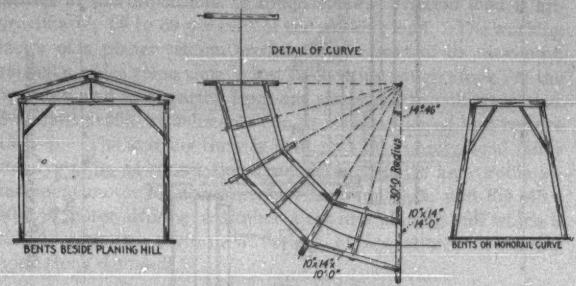


FIG. 40—MONORAIL STRUCTURE DETAIL

type are used by some of the larger mills. Fig. 42 shows a representative installation of this character. All of these installations have shown a very satisfactory saving in the expense of handling lumber.

PLANING MILL

As before mentioned, the material for this mill has usually been subjected to a drying process—either natural or artificial. All of the machines are designed for constant-speed drive, the variations in rate of speed being accomplished by changing the sizes of the feed roll driving pulleys. A general planing mill layout is shown in Fig. 43.

Power demands of planing machines have increased somewhat in the last few years, due to the development of fast-feed planers. This increase, however, has not been accompanied by a corres-

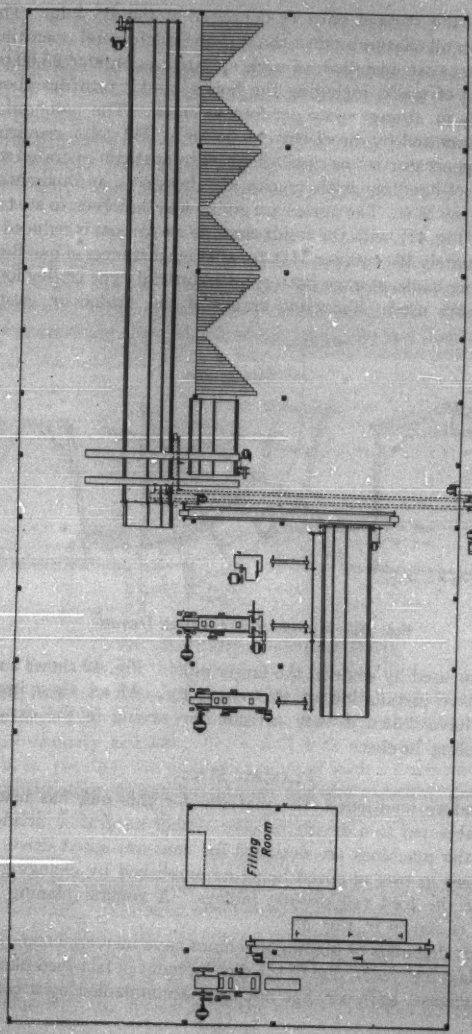


FIG. 43—PLANING MILL LAYOUT

ponding increase in motor sizes, as the present tendency is to utilize more fully the rated capacity under usual conditions, operating the motor at overloads when handling the heavier stock. It is universal practise to directly connect constant-speed, squirrel cage motors to the machine driving shaft, using a flexible coupling. Profile attachments are more conveniently operated by an individual motor driving the two profile cutting heads.

The starting duty of planers is rather severe, due to the large masses to be accelerated to high speeds. To this is traceable the common fault of "over-motoring" which was so much in evidence with the older, medium-feed machines. The advent of welded end-ring rotor construction has removed this obstacle.

The running load is fluctuating according to the small irregularities in the dimensions of rough stock. Friction load is approximately 55 to 60 per cent of the working load. The working factor of a planer seldom exceeds 60 per cent of its maximum capacity, since some time is lost in locating rough stock for the operator, and in changing from one size stock to a different size. Standard profile attachments run at constant speed and require 15 h. p. The starting duty is light and the running load fairly steady. Fig. 44 shows the main driving motor and profile attachment motor for a modern fast-feed matcher, and Fig. 45 a 60-h.p. motor driving a timber sizer in a planing mill which is called upon to perform a variety of operations, depending upon stock demands.

Combination Matcher and Re-Saw

On orders which will permit one side rough, the re-saw simply splits the stock after it has been properly surfaced. The power requirements of the matcher end do not vary from standard machines. The re-saw (diameter of wheel 54 in. or 1.37 m.—saw blade 7 in. or 18 cm.) requires 35 h. p. to drive it. The motor is mounted on top of the re-saw frame and its weight is supported by a counterweight from a sheave attached to the ceiling. The best method of drive for a re-saw so mounted is by a silent chain. The matcher end requires a 50-h. p. motor. (Fig. 46).

In isolated instances, fast-feed matchers have been fitted with individual motors for driving the various elements of the machine, *i.e.*—one motor driving the feed rolls and one for each cylinder or knife drum, etc. A modern fast-feed planer, size 6 in. by 15 in., feeding 200 to 250 ft. per min., requires motors as follows: top cylinder geared with cloth pinions to a 35-h.p. motor,

bottom cylinder to a 20-h. p. motor, side heads to 15-h. p. motors, feed rolls to a 15-h.p. motor.

Such refinements have shown an actual saving in energy over the one-motor method, since all belt friction and slippage is eliminated. The high speeds required for the various parts of the machine, some of which do not fit standard speeds of a 60-cycle motor, made it necessary to resort to gearing with cloth pinions. Very satisfactory results have been obtained.

After being finished, the product from the planers is trimmed to remove defective portions; it is then sorted and bundled. Old practise required a trimmer table with a swing cut-off saw (Fig. 47) for each machine, the output being handled by hand after leaving the machine. Their work is very intermittent and the starting load is light. Squirrel cage, constant speed motors are used, the usual size being three h. p. Tests of a 20-in. saw follow:

Running light	1.2	kw. input
Cutting one 2 x 4 in.	3.8	" "
" two 2 x 4 "	4.8	" "
" three 2 x 4 "	7	" "
" one 2 x 6 "	5.1	" "
" one 2 x 12 "	6.2	" "
" one 1 x 6 "	2.7	" "
Approx. load factor	30	per cent
Demand factor	300	per cent.

The duration of a cut is very short, otherwise the size motor ordinarily employed would have to be materially increased.

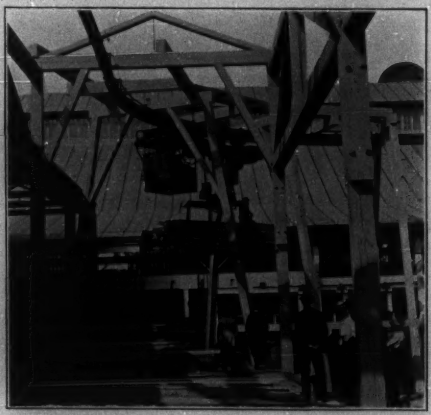
The advent of fast-feed planers and matchers necessitates a greater capacity method of handling the output without entailing a too great labor addition. The scheme adopted is to group all planers so that their output falls upon a transfer table. At the end of this table is installed an automatic trimmer similar to but smaller than the saw mill trimmer. In this way one man can trim the entire output. A squirrel cage constant-speed motor furnishes a satisfactory drive, 25 h. p. being the average size motor adopted for this service.

The transfer tables and refuse conveyers in a planing mill are usually operated by back-geared wound-rotor motors with chain drive. The material to be handled is very light, requiring at maximum three- to five-h.p. motors for such service. (Fig. 48).

Besides the trimmings, the other refuse from the planing mill consists of dust from the saws and shavings from the planers. The sawdust and shavings are cared for by air suction and blower systems (see Fig. 16 for typical layout). Usually

[WHITNEY]

FIG. 37—VIEW ACROSS LOG POND, SHOWING REFUSE BURNER



[WHITNEY]

FIG. 38—MONORAIL CAR WITH LOAD FOR DRY KILN

[WHITNEY]

FIG. 39—MONORAIL CAR AND TRANSFER CRANE FOR SPOTTING CAR AT DIFFERENT SECTIONS OF SORTING TABLE

FIG. 41—STORAGE BATTERY TRACTOR [WHITNEY]

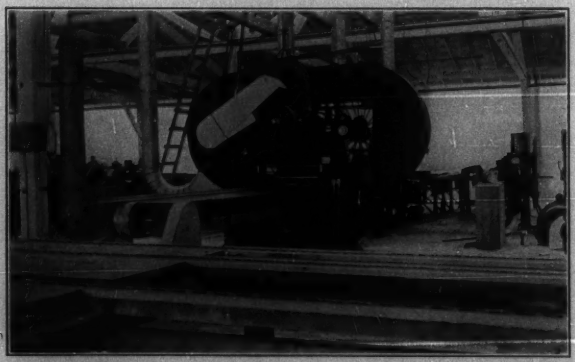
[WHITNEY]

FIG. 42—FOUR-TON MONORAIL LUMBER-HANDLING CANTILEVER CRANE, 106 FT. TROLLEY TRAVEL, HAMMOND LUMBER COMPANY, ASTORIA, ORE.

[WHITNEY]

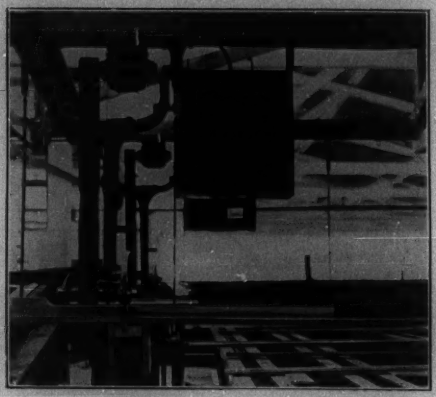
FIG. 44—MATCHER WITH 50-H P. MAIN MOTOR AND 15-H.P. PROFILE ATTACHMENT MOTOR

FIG 45—TIMBER SIZER [WHITNEY]



[WHITNEY]

FIG. 46—RE-SAW END OF COMBINATION MATCHER AND RE-SAW, WITH MOTOR MOUNTED ON RE-SAW FRAME AND DRIVING BY SILENT CHAIN



[WHITNEY]

FIG 47—SWING CUT-OFF SAWS FOR TRIMMING PLANING MILL STOCK

[WHITNEY]

FIG. 48—SORTING TABLE DRIVE IN PLANING MILL, WITH BACK-GEARED MOTOR

[WHITNEY]

FIG. 49—DOUBLE 60-IN. EXHAUST FAN DIRECT-CONNECTED TO MOTOR

[WHITNEY]

FIG. 52—INTERIOR OF SHINGLE MILL USING ELECTRIC DRIVE. THE COMPACT MACHINES AND ABSENCE OF TRANSMISSION BELTING IS IN MARKED CONTRAST TO THE CROWDED APPEARANCE OF BELT-DRIVEN MILLS

the trimmings are put through a small-capacity hog and then handled by the same blower system, or conveyed to a wood bin for the local wood market.

Refuse Exhaust System

Ordinary centrifugal fans capable of giving 5 oz. pressure are commonly used. Motors are sometimes direct-connected to the fan impellers, but more often belted, since with the latter arrangement the speed of the fan can be changed from time to time to get the correct pressure required in the system. With direct-connected fans, the impellers are ordinarily pressed directly on the motor shaft extensions, the motor bearings caring for the slight additional weight of the fan impeller. Fig. 49 shows such an arrangement. Constant-speed motors are used for this service. The load is practically constant throughout the operation, and is slightly less when the planers are working than when idle, provided of course that the suction intakes are left open at all times. Double fans are ordinarily used, one side lifting the refuse and the other side blowing through the pipe line to the fuel bin.

It is common practise to install a simple low-pressure gate in the suction to each machine, so that that particular intake may be isolated when the machine is shut down, thus reducing the energy required.

The following is indicative of the average power requirements of fans under usual conditions, length of pipe line, intake openings, etc., being assumed normal:

Single 40-in. fans	20 h.p.
" 50 " "	25 "
" 60 " "	35 "
" 70 " "	50 "
Double 40 " "	35 "
" 50 " "	50 "
" 60 " "	75 "
" 70 " "	100 "

Another system which has proved economical in energy consumption makes use of a low-pressure centrifugal fan for suction only, and uses high pressure for blowing the dust through the pipe line to the fuel bin. With centrifugal fans used for both suction and blowing, all of the material handled is passed through the impeller itself, necessitating large clearances and a consequent loss in efficiency. With the high-pressure system, none of the dust or chips passes through the fan itself, but the discharge from the collector empties into a revolving drum with vertical

cylindrical compartments. The cylindrical cartridges thus formed are forced through the pipe line as each compartment revolves under the compressor discharge. Centrifugal compressors and positive pressure blowers find a wide field in the high-pressure system.

Shingle Mills

Figs. 50 and 51 show the latest tendency in the layout of shingle mills. The logs are handled in the same way as in a saw mill, after which they are cut into bolts, which go to the shingle machines and are finally trimmed, sorted, bundled and dried. Fig. 51 gives the main floor plan of an electrically driven mill, while Fig. 50 shows the elevation of a later mill. The latter was originally planned for steam drive, but later changed to electric, so that the elevation shows a line shaft in error. In the final plans, this was eliminated and the driving motors connected to the shingle machines, as in Fig. 51. Fig. 52 shows the shingle machine floor of this mill, which is the first, of which we have record, using individual motor drive throughout. Its operation has been very satisfactory. Of all the machines used in these operations, only the shingle machines, shown in Fig. 52, differ from those already described for other operations.

The standard upright shingle machine requires two motors for its best operation—a 20-h.p. motor driving the main saw and mechanism and a 3-h.p. motor driving the trimmer saw—both constant-speed, squirrel cage motors direct-connected to the driving shafts. The power requirements of the complete machine—both the shingle saw and the trim saw—are about 18 kw. input, no-load, and 20 to 21 kw. input when cutting.

General

In general it is estimated, in a mill using steam engines with line shaft drive, that 8 to 10 h.p. per M feet b.m. capacity per 10-hour day, is required for the sawmill machinery only. This old rule-of-thumb method was close enough for practical purposes, since with maintained steam pressure the engines had large overload capacities, but with very poor speed regulation. This poor speed regulation is noticeable in almost all steam-driven mills. The friction load is enormous, requiring often 40 per cent of the rated engine power when running the mill idle.

With the advent of electric drive, the motor horse power installed will approximate 11 to 13 h.p. per M feet b.m. capacity per day, for both sawmill and planing mill.

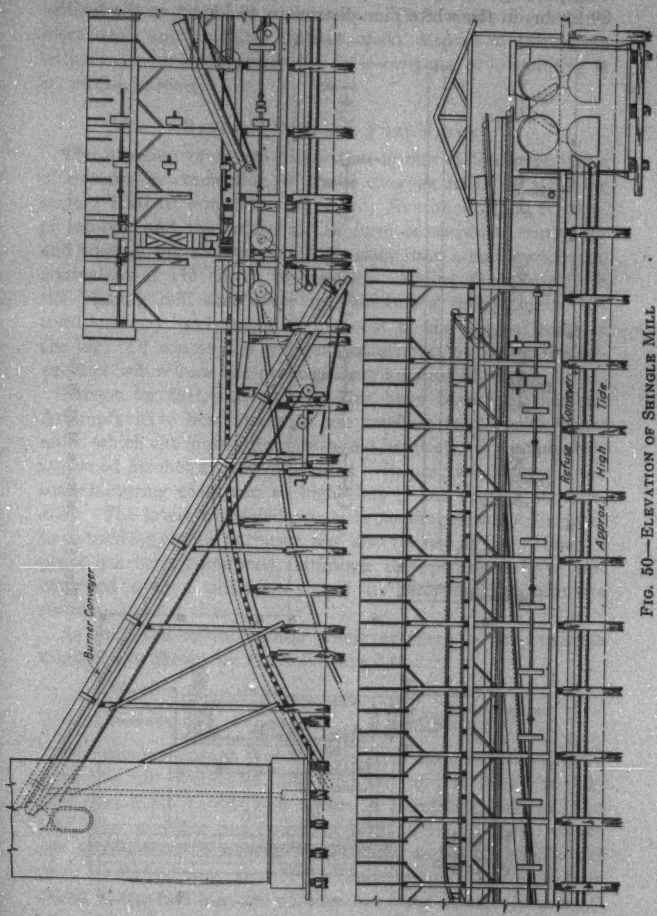


FIG. 50—ELEVATION OF SHINGLE MILL

The energy required for manufacturing 1000 ft. b. m., including planing mill operation, has been found to vary from about 29 kw-hr. in the white pine district to 46 kw-hr. in the fir dis-

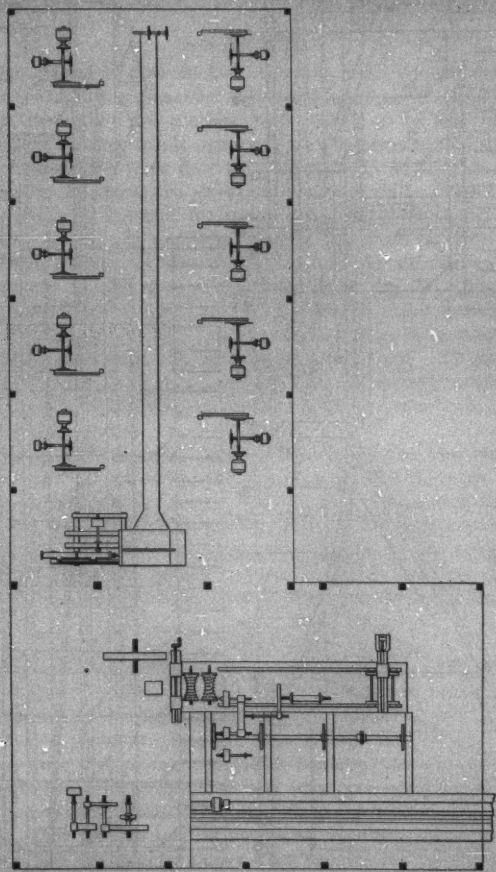


FIG. 51—SHINGLE MILL PLAN

trict of the Pacific Coast, which would indicate an actual electrical horse power of from 3.8 to approximately 6 h.p. per M feet daily capacity of an electrically operated mill.

The cost of power to the average saw mill operator means very little, due to the large wastes which they must experience in their manufacturing operations. Those mills located remote from any available market, must dispose of this waste either by generating power for their own use or consuming it in refuse burners.

Refuse—Uses and Fuel Value

The question of refuse disposition is one of the large items of expense in connection with the average mill. A solid log scaling 1000 ft. b.m. will, when cut, give about 1150 ft. b.m. of lumber, and the refuse in the form of sawdust, trimmings and edgings will amount to a little more than a half cord, or the equivalent of 115 cu. ft. of cut fuel. Adding the refuse from the planing mill and other manufacturing departments, the total loss may easily reach 40 per cent of the original scale of the log. Of course the greater refinements in using the by-product will reduce the proportionate amount of refuse.

Except for fuel, the uses for this have been very narrow. Attempts have been made to use sawdust from Pacific Coast mills, which cut mostly fir, spruce and hemlock, for manufacturing wood alcohol and ethyl alcohol. In practise, however, the manufacturing costs run so high that it has proved unprofitable. The latest projected use is in making sawdust briquets to be used for paving purposes, and also for use as fuel. Such a plant has been completed, although its operations have not extended over a sufficient period to determine the ultimate success.

As fuel, the refuse values, wherever there is an available market, are shown by the following data:

Wt. one cu. ft. wet sawdust	21 lb.
Per cent moisture	48 to 52 per cent.
Heat value per lb. wet sawdust	3500 B. t. u.

Wet sawdust means that in its natural state coming directly from the mill operations, and includes cut fuel from the hog. The dust from planing mill operation is relatively dry, and as fuel, has a value per pound of 8500 B.t.u. These values are averages of a number of analyses and apply to sawdust from mills cutting mostly fir and spruce. As ordinarily found in the fuel bin, the mixture has some intermediate heating value. Sawdust is usually sold in units of 200 cu. ft., the equivalent of about 0.88 cord of slabwood

Slabwood is cut to 4-ft. lengths and sold by the cord. It also has a wide use as fuel, though as such it is more expensive than sawdust.

The following table gives the average values of wood fuel as compared with oil and coal, the costs of the various fuels per unit being assumed as in column five. Column two gives evaporation values taken from tests at the same plants, using the fuels named.

	B. t. u. per lb. dry fuel	Lb. water evaporated from and at 212 deg. per unit.		Cost per 1000 lb. water from and at 212 deg.	Cost per unit of fuel
Sawdust.....	8,500	(200 cu. ft.)	10,500	9.5 cents	$1.00, 200 cu. ft.
Slabwood.....		(1 cord)	12,500	24 cents	3.00, 1 cord
Split cord wood...		(1 cord)	13,500	37 cents	5.00, 1 cord
Oil.....	18,500	(1 lb.)	15	21.9 cents	1.10 per bbl.
Coal.....	11,000	(1 lb.)	7.2	41.6 cents	6.00 per ton

DISCUSSION ON "ELECTRICITY IN THE LUMBER INDUSTRY" (WHITNEY), SPOKANE, WASH., SEPTEMBER 10, 1914.

Mr. Scott: Mr. Whitney's paper is of particular importance to central station men because it shows that there is a field for prospective business open that is usually placed in the same class with steam laundries, that is to say, absolutely unapproachable. I have never dealt directly with any logging men, but have had occasion to attempt to sell power to a few sawmill men, particularly for small plants, none of very large capacity, and their main objection to motor drive is, first, they claim the first cost of the motor installation is excessive as compared with a steam engine; and, second, they say that the motors will not stand up to the work. Now, never having actually seen a drive of that kind I was not in a particularly advantageous position to refute their statements. Third, they say they must have steam anyway for their dry kilns and for their log-carriers, and therefore there is no particular advantage in putting in electric drive. And lastly, they say that they are forced by law to get rid of their waste; in most instances they are too far removed from a point where the waste can be sold as fuel, so they have to install a burner especially to get rid of it, if electric drive is used.

Now, I would like, if possible, to hear some arguments that could be put forth to refute those points of view. So far as central station service is concerned, compared with isolated plant service in sawmills, I should unhesitatingly say that, for an installation having over, say, 1000 e.h.p., central station service could complete with an isolated plant very favorably, provided the sawmill was within a reasonable distance of a transmission line. For mills smaller than that I have not seen enough data to be able to tell.

On page 1323, where a comparison is made between operation of logging railways by electricity and by steam, a saving of about $20,000 a year in favor of electricity is shown. I should think that any logging man, no matter how skeptical, would "sit up and take notice," and at least inquire how that could be done.

There is another question in regard to a sawmill: whether steam operation is less efficient from a time standpoint than a motor drive; in other words, whether more time is saved by motor drive than by steam. When a man drives a headsaw with a steam engine and runs into a stiff cut, the steam engine begins to show signs of distress and slows down, and he eases up on his speed; but with a motor the log goes right straight through. I have had that point put up to me two or three times by sawmill men and they claim it is a fact that there is only one thing for the motor to do under such conditions, and that is to blow the fuses. If I understand Mr. Whitney's paper correctly, the development of the electric motor in the last few years has reached such a point that these difficulties are overcome.

A. A. Miller: Last year at the Vancouver convention Mr. E. J. Barry presented a paper on *Logging by Electricity*, and Mr. Whitney contributed very largely to the discussion. It is apparent that Mr. Whitney has been busy during the past year in collecting further data, which have been very systematically assembled in this paper.

I can remember distinctly that only a few years ago loggers and lumbermen in general would not pay any attention to the proposal to use electricity in their operations. The progress made has been very marked, and no up-to-date designer of sawmills would now entirely pass up consideration of electric drive, but would give it very thorough consideration, and in a fair percentage of cases would determine upon electric drive in preference to the old type.

With respect to the question which Mr. Scott asked as to the difficulty encountered in steam drive where the speed of the carriage is diminished in order to allow the saw to speed up again, and where in case of electric drive it is not so regulated but is allowed to go forward at practically constant speed regardless of the load on the motor—this is due to the inherent ability of the motor to carry, temporarily, heavy overloads, and to give such power as is required to take care of the load that may be imposed upon it. That is somewhat allied to the advantage of electric locomotives, in heavy freight work, over steam locomotives, in that for short intervals the capacity of the electric machine is only limited by the amount of power which you can deliver to it. Induction motors, both of the squirrel cage and wound secondary type, for a number of years past have been designed on sufficiently liberal margin to stand tremendous overloads for a period of a minute or so.

F. D. Weber: About seven or eight years ago, I think, the first electrically driven sawmill in Oregon was installed at Dee. Prior to that time there were absolutely no data on this subject. The mill was fitted with all standard squirrel cage motors, with a 150-h. p. squirrel cage motor placed on a double-cut 8-ft. band mill, and after it was installed it was impossible to start the band mill. The only way which they had to start it, and this method was used for years, was by putting a 4 by 4-in. timber in the upper flywheel and having six or eight men throw their weight on it.

A little river runs within about a thousand feet of this mill, and upon this was installed a hydroelectric generating plant to furnish power for the mill.

When this mill was installed they had no consideration at all for sizes of copper, the mill men installing all the wiring. The writer ran tests under operating conditions and found that the copper was about one-half the proper size for satisfactory operation. There was also trouble with the motor connected to the trimmer. This motor was not of sufficient size and necessitated the shutting down of the trimmer occasionally to allow the motor to cool off.

This lumber mill is owned by the Eccles interests, and they were so impressed with the operation of the first mill that when it burned down about two years ago, they replaced it with another electrically operated mill, although it was impossible with their first equipment to operate the band mill double-cut, because when thus operated the motor was unable to carry the load.

There are some questions which I would like to ask Mr. Whitney:

First, have manufacturing companies ever considered furnishing an enclosed type of motor in certain locations in sawmills? After a sawmill has been operated electrically, this blower system that Mr. Whitney spoke about generally fails to keep the mill clean and a great deal of refuse collects, such as sawdust and chips, to which the motors are exposed, consequently a question of fire hazard arises. I have seen motors completely covered with chips and sawdust.

Second, in regard to the motor of the main carriage, I would like to know whether they have had any trouble keeping oil in the bearings of this motor. I should imagine that it would splash out.

Third, I desire to know whether there have ever been any tests made on the load factor of this mill or any other mill.

Fourth, have there been any figures presented concerning the relative cost of installation of electrically driven mills as compared with the first cost of motors? I have heard the argument advanced that the cost of wiring a modern mill is excessive.

Fifth, are there any data concerning the life hazard in logging woods in connection with electrically operated logging engines? It has been said that this hazard was considerable in dense timber where cutting was taking place continually, which might interfere with the transmission lines. Also, the connection between the portable transformer stations and the logging engines, being subjected to the various accidents of the logging woods, might expose the men to live circuits, and produce a serious life hazard.

J. B. Fisken: I want first of all to note that, if I mistake not, the first article in any of the Institute PROCEEDINGS on the subject of the application of electricity to the lumbering industry was a paper by Mr. E. J. Barry, *Electricity in the Lumber Industry*, presented at Los Angeles in April, 1911. Three years later we get a paper from Mr. Whitney, which seems to me as if it might almost be the last; there may be some small improvements, but from what Mr. Whitney tells us the subject has been pretty nearly covered.

There still remain a few things to be done. The question of drying the lumber will involve the generation of steam unless there is a hydraulic plant available; if there is, the drying of the lumber might be done by electricity. The log carriage is not electrically driven in the case we are considering; the operating man might have difficulty in taking care of that. I think it is

a question for the manufacturers to solve. The problem of disposition of refuse is a hard one, but in these days of conservation it would seem that some means might be found to take care of this refuse; it must have some commercial value, and unless the cost of saving it is more than the market value, it should be taken care of.

From the standpoint of the operating man, I think the load would be an objectionable one for the reason that it would be very intermittent and severe. Mr. Weber has asked a question regarding the load factor. In the item of costs on page 1320 Mr. Whitney puts in coal at $4.25 a ton. From conditions as I know them I doubt very much if coal could be laid down at the donkey engine for anything like $4.25 a ton. It costs us more than that to lay it down here in Spokane, and to haul it up to any of the logging plants must add very materially to the cost.

Mr. Whitney discusses methods of handling and conserving the refuse. That is a matter, of course, more for the commercial man than for the engineer; at the same time the engineer should work with those who can settle it, and I hope before long to see the sawmills and wood-working factories entirely operated by electricity. I think it is almost invariably the custom now in putting in a large mill to put in electric drive. We have service in this neighborhood that is typical, and from what I have been able to learn the owners would never think of changing back to steam drive.

L. T. Merwin: There is no question in my mind but that the difficulties due to peak loads in sawmill operation can be successfully worked out. Following actual experience of a number of years in electric hoisting under rather severe conditions, I do not think that the question of extreme momentary demand will remain a serious one, even though at the present time it may seem so.

I want to ask a question of Mr. Whitney bearing on the point that Mr. Weber and Mr. Fisken have already brought out, the poor load factor, the highly fluctuating load and the extreme peaks. Has any consideration been given to the handling of these extreme peaks in a manner similar to that in which extreme peaks of mining loads are handled, as, for instance, by some sort of modification of the Illgner system or by a heavy flywheel set operated by an induction motor? Mr. Whitney mentioned in his paper that of necessity the old manner of running steam-driven mills was from one central drive; I gather that from that they went to the other extreme when first installing electrical drive, and finally have come back to a compromise, with partly group drive. If the flywheel system as applied now to extreme peaks of mining loads can be applied to the sawmill, would that not break down the objections of the central station operating engineer?

Mr. Cheek: As the variable loads that necessarily come upon a motor, it seems to me, would make its protection a very diffi-

cult matter, I ask Mr. Whitney what he recommends for the protection of such a motor, whether fuses or other automatic devices. I also ask how the size of the copper is calculated, and whether he has any further information with regard to tests.

I was up in Victoria not long ago and there is a new plant up there that had recently been equipped for making briquets, and they used the refuse, they used the sawdust and also the slabs after going through the hopper; and they claimed that these briquets burn slowly and with much the same characteristics as coal and compared quite favorably with coal.

The matter of the decrease of the fire hazard in logging is a point which I think will act very much in favor of electrical donkeys. This last season was a very dry one and some companies suspended operations during the dry season because of the severe fire hazard of the steam donkey.

A. Norman: The company with which I am connected recently began to supply power to a large sawmill. This mill started in actual operation about three weeks ago, and the mill being entirely new and all of the machinery new, they have not as yet had a full day's operation, and I would not attempt to say just what the load factor will finally be when the mill is in constant operation. However, I could say in a general way that we believe it is going to be about 50 per cent. We feel very much encouraged as to this particular installation, the mill people feel very much encouraged, and I think it offers a fertile field for cooperation between the milling industry and the central station.

In our case, we were so situated that we could furnish this mill not only current for the operation of its motors, but also the steam needed for the dry kiln and for such other purposes as they found it advisable to use steam for. In an installation of some 2100 h. p. in motors I believe we are furnishing them some 225 h.p. for their steam needs. As I say, this installation is so new that we cannot give very full information, but we would be glad to have anyone who is interested in this subject either come to Eugene or Springfield and look into it, or write to us after a brief period, when we expect to get some very definite data, and our company will be very glad to give you any information we have or can get.

W. H. R. Fraser: The largest mill we have connected with our system is probably a good deal smaller than that which Mr. Norman spoke of. The largest mill, I think, has something like 750 to 1000 h. p.; the mill is about nine miles from the nearest substation and is also fed in connection with the same line feeding a town. So this is not a mill line alone, but also a lighting line. We have had no complaint regarding the fluctuation of voltage, so that it cannot have been very bad.

In regard to the utilization of refuse: one mill that I know of has been experimenting with briquets, but whether successfully or not I cannot say. Another mill until recently was trying to produce turpentine from sawdust of certain woods, but that has been a failure.

The question of supplying power to very large mills could scarcely be considered, unless very favorably located. One of the largest mills in the world, for instance, has a total capacity of one and three-quarter million a day; driven by individual units; we could never offer them power at a rate that they could consider in preference to installing their own plant; if we delivered power to them we would have to have a 30,000- or 40,000-volt line installed and substations, and by the time we did that the cost of the power to them would be so great that it would be prohibitive.

Another point: I believe that Mr. Whitney mentioned something about coke. I do not think there is a single sawmill in British Columbia using coke today.

F. D. Weber: I remember seeing a note in some trade journal in which it mentioned that there has been a process devised of drying lumber in the open air by the use of quite an appreciable amount of current at low voltage, by simply stacking and separating the layers of lumber by wet carpets. I would like to know if anyone knows anything further on this subject. I understand that is done in Australia and some places in England. If that is the case it seems to me that would solve the question of the dry kiln.

John Harisberger: I may be a little optimistic in regard to companies operating hydroelectric plants selling power to sawmills to their mutual benefit. On our system in the Puget Sound district, we have several mills which have proved quite satisfactory, from both a commercial and an operating standpoint. We also furnish all the power for two coal mines, amounting to 1100 h. p., and several other mines are considering taking our power. I have had some experience in the early days when attempts were first made to operate sawmill machinery by electric motors. The main difficulty was to get sufficient information so as to determine the proper size motors to install. This is entirely different now, as manufacturers of electric apparatus and central station people have accumulated a great many data on such applications, so that it is no longer a question of experiment.

E. F. Whitney: I am rather disappointed at the lack of optimism; at the same time I am pleased at Mr. Harisberger's expression that he does look forward favorably to the use of central station power in the sawmills. It can be used, and under certain conditions it can be put in and can operate as cheaply as one can generate and supply his own power, but you must first convince yourselves that it can be done and afterwards convince the mill men. There is always the question of cost of installation and cost of operation.

To begin with the cost of the motors: I have recently completed, in connection with a mill architect, two estimates for entirely different types of mills, one a single-band mill and another a double-band mill, together with the planing mill. Com-

plete estimates were made, first, using steam drive, and second, using electric drive, for each type of mill. The electric mill included the necessary generating station, on the assumption that power would be derived locally from mill refuse. We were surprised to find that for the sawmill alone, electric drive proved lower in first cost—installation cost—than steam, and this without including the planing mill. This latter would have made the balance even greater in favor of electric drive. There is no difference of opinion as regards the very much lower operating and maintenance cost of an electrically driven sawmill.

This of course was an individual case and was figured on its own merits. You will have to let by-gones be by-gones and not consider those mills designed and built along the old lines of steam drive with line shafting and belting and motors placed here and there wherever a drive was needed. The mill must, to get best results, be laid out with electric drive in view, and full advantage taken of its flexibility. We now know what can be accomplished, but the results come only after careful and correct installation and not by chance.

A mill requiring approximately 2300 or 2400 h.p. usually has over 20 separate and distinct engines scattered around its plant; it must have high-pressure steam lines to each one of these engines; the largest would be about 800 h. p. and the smallest about 25 h.p.. There need be no further comment than that engines used under such conditions are very uneconomical steam users. An item which is lost track of is the boiler capacity that is required to supply such an installation, and the large initial cost and high upkeep cost of the steam-generating equipment. Electric drive would reduce it at least one-half.

Regarding the ability of the motors to stand up to the work: I recall an instance of a blower, with impellers 80 in. on one side and 70 in. on the other, pressed upon the motor shaft extensions. The motor was rated 100 h. p., 720 rev. per min. The motor did the work satisfactorily, but in the course of an investigation just to see how much power the blowers were taking we found that while the blower specifications called for 96½ h.p., 147 h.p. was the output of that motor, day in and day out, ten hours a day, five hours in the morning and then shut down one hour at noon and then five hours in the afternoon. In this case the motor was in at the top in the planing mill, which is always a well-ventilated structure, it had good cooling air, and the working capability of the motor was increased considerably above what might have been found in a more unfavorable location.

With the present successful mills operating with electric drive, with the proposed largest mill on the coast preparing to use electricity throughout, there can be no question as to the economy of this method or the capability of the electric motor to do the work efficiently and successfully.

The point has been brought up that they must always have steam in the mill. Granting that they must have steam for

some uses, there is no necessity for them to have the quantity of steam equipment that will be necessary in all cases except with electric drive.

Upon the question of production: This is the one subject which sawmill men are glad to discuss and consider at any length. They appreciate that their only hope of salvation is to cut down their costs of production. I have known many instances of steam-driven mills where the lag in the steam engine during the cut in the main headsaw is as great as 30 per cent. I have seen the edger lag fully as much. That simply means that they are losing so much productive time. This is unknown with motor drive. Practically all of the motors are squirrel cage type—with a few exceptions, such as the one driving the headsaw; the only reason we use a wound-rotor motor there is because of the limited generating capacity in the average sawmill and to limit the current input at starting. Its characteristics are of course practically the same as the squirrel cage motor after it is up to speed, and any squirrel cage motor would absolutely reach its breakdown point before it had any such regulation as that, unless of a special design. The automatic overload protection and ability to stand up under varying load conditions has already been spoken of. This is an important item when we are driving, for instance, a refuse conveyer. That is probably as severe a drive as any in the mill. With steam drive from the main shaft, if the conveyer should stick, as with a slab jammed under the chain, something must break to clear the trouble. This means lost time, and repairs. With electric drive, we might have the conveyer pretty heavily loaded at times, but of course the relay would be set to care for a predetermined overload with a reasonable time limit, and any more severe condition than that for which it is set should trip the motor out of circuit, and relieve the transmission machinery of the severe strain, saving the breakage that would otherwise occur.

The question of maintenance of voltage was touched upon by Mr. Weber; it is one of the most important points in connection with the operation of electric logging engines. The substation must be 200 to 1000 ft. from the location of the engine itself; in the beginning of the operation it may only be 200 ft., but as the work is extended and the donkey gathers the close timber it will probably be, at the next step, 1000 ft. away. The duty is heavy, often requiring the motor to exert very close to its maximum torque, so we must take the precaution to see that good voltage is the rule at the terminals of the motor. This of course applies to sawmill machinery as well, because we cannot get the maximum productivity unless we maintain our speed and capability to care for heavy loads suddenly applied.

In regard to the question of fire hazard and enclosed motors: This is really the reason that squirrel cage motors are so universally used. In such motors the bearings of course are practically the only source of fire risks. The motor bearings should

give very little trouble, and after once being in good condition should require very little attention.

Enclosed motors were never seriously thought of. As to the possibility of dust and chips getting in the windings, the ventilating scheme which has generally been adopted in the manufacture of motors is such that the air comes out through the laminations of the machine and will tend to remove any dust that would clog up the ducts or get into the windings through them. Of course, it would be possible to cover the motor with chips and dust and it would still be operative. The air lines are distributed pretty well around any sawmill at the present time, so that if for the moment any machine shuts down the operator takes his air hose and blows all the dust and chips away. Where it is necessary to use the slip ring type of motor, of course the slip rings should be enclosed. There is a possibility of sparking at starting, and until the motor is up to speed, and it is common practise to enclose them.

On the log carriage some slight trouble has been experienced with oil spashing out of the set-works motor bearings. The rate of acceleration of the log carriage at each end of its travel, particularly at the beginning of its return, is very high, but with reasonable precaution, oil-throwing trouble can be remedied. In fact, the first set-works motor used was strictly a standard motor, and no trouble was ever experienced with oil splashing out.

In regard to the load factor of a complete mill, we usually assume the demand factor of an electrically driven mill as 70 per cent, in kilowatts, of the connected load in horse power, and the load factor as about 70 per cent. In other words, if you have 1500 h.p. installed, about 750 kw. would be the average load on the mill. I have detailed records of two complete sawmills in the Northwest. One of them has a load factor of 57 per cent. The demand factor is 83 per cent. The average cut per day is 115,000 ft. b.m. The highest peak recorded in any ten minutes was 1150 kw., and the maximum demand for any ten-minute period was 940 kw. The other is a group-drive mill, with 1300 h.p. connected; the load factor is 65 per cent, and the demand factor 88 per cent. The daily cut is 121,000 ft. b.m. (as we would expect with the group drive, a smaller connected load has a larger cutting capacity); the highest peak for any ten-minute period was 1000 kw., the maximum demand for any ten-minute period 850 kw.

The prevailing power factor, I suppose, if we take all of our mills, is roughly 70 per cent; some mills run as low as 50 per cent, some mills run as high as 85 per cent. I have records of a mill which has been in operation for some two years, whose power factor throughout the day's operation never gets below 74 per cent, and there are times when it goes up as high as 85 per cent. That is an extremely high point for a typical induction motor load.

The greatest drawback to the maintenance of a high power factor in sawmills is the small number of large motors that must necessarily be used, which, during a great portion of the time, must certainly run at very light load. Though not less than 200 h.p. is required on the average edger, and a motor somewhere in the neighborhood of 250 or 300 h.p. on the head-saw, the loads averaged per day for these machines will be about 50 and 100 h.p., respectively. The great majority of group drive installations are, as a rule, well loaded and run at good power factors and at good efficiencies. The planing mill equipment has a very fluctuating load; during a portion of its load it runs at a relatively low power factor and low load factor. On the average, a mill of about 2100 h.p., such as Mr. Norman spoke of, under general operating conditions will have a load factor varying from 65 up to 80 per cent. The particular mill of which he spoke has 74 motors with a total of 2053 h.p. connected: the sawmill has 52 motors with 1645 h.p.; the planing mill 18 motors, with 340 h.p. The daily kilowatt-hour consumption had been estimated at from 7500 to 8000 kw-hr. With operations well under way, these figures were confirmed.

As regards the cost of wiring a sawmill installation, that depends largely on the individual. A mill man can put in a wiring job that will equal or excel that in any high-class city office building, or he can put in simply a substantial wiring job that will be satisfactory for his service. There is a difference in cost of, I suppose, 250 per cent. In making up the comparative estimates that I have already spoken of, for steam drive and electric drive, these estimates were based on giving the electrical installation the worst of it in every case that we possibly could, and so we figured on conduit wiring throughout. Even then the wiring cost amounted to about $5500, I think. We had about $9000 which we could have used for this and still come out equal to steam drive.

The fire hazard in the logging industry is something that would have to be given consideration. That, of course, is always brought up whenever the subject is broached to loggers. There is no reason why electrical equipment that is operating a logging camp cannot be as cheaply and as safely handled as it can be in any of our generating stations. The transmission line usually runs along a railroad right-of-way and is just as well protected as any other power company's transmission lines. From it branches are run, depending upon the size of the company's operations; from the substation an armored cable leads out along the ground to the logging engine itself; the cable used is typical submarine cable, which is perfectly safe.

In regard to the question of electric drive for the log carriage: Suppose, for instance, we look at the typical operating cycle of a log carriage given on page 1331. Even with a log of only 1500 ft. b.m. you have a total weight of 38,000 lb., about 19 tons; the requirements of mill operation do not allow the carriage

to lag any more than is necessary, and the average speed is about 250 ft. per min. in the cut. That is based, of course, on a single-cutting band mill. The average speed of return is about 650 ft. per min., and we must accelerate that outfit to that speed and maintain it at least for a portion of the travel of the total distance, varying, say, from 40 to 50 ft. as an average. There is not much travel but it is high-speed work, the acceleration is fast—in fact it is all that a person can do to stand on the log carriage and maintain his balance. A log of 1500 ft. b.m. is by no means the heaviest load, it is about an average. If we should get a log of about 5000 ft., or about 40,000 lb., on, it would run the total weight up to something over 35 tons that must be handled at this speed. The common method is by a twin-cylinder, simple steam engine, which operates a drum. The engine, complete with its equipment installed, costs about $3000 to $3500. Any electrical scheme that can compare favorably with it in first cost and in ultimate cost, including operation, will undoubtedly meet with favor from the sawmill people. They would like to do away with the engine, but nothing to compete with it has been shown up to the present time.

The coal and other fuel costs as given on page 1320 applied to logging, not to sawmill operation. In the logging industry they have realized they were burning good merchantable timber as fuel, as the logs cut up and burned under the donkeys must be the very best or they will not split, and on account of the grade of timber they have to use, they have attempted to use oil and coal. Some camps have run comparative outfits to get data on the results accomplished by the use of the various fuels.

In regard to Mr. Fisken's suggestion that additional uses for the refuse be given, and that nothing be said about burners: I attempted to take the point of view of the man who was fully informed about the electrical side of the question but knew very little of a sawmill or its workings. Of course it is necessary for the sawmill operators to dispose of the refuse, because there is too much of it for their own power demands, and this must be got rid of in some way. Usually it is burned in the burners, and they are a source of expense.

I have touched upon the load of the whole mill. I might say that the two cases cited applied to fir districts. In pine districts the load is very much lighter, the connected horse power, we will say, in one case, being 1900 h.p., the load factor only 46 per cent and the demand factor 67 per cent, an average daily cut of 350,000 ft., with a maximum demand for ten minutes of 800 kw. and the highest peak in any ten minutes 950 kw. That is in marked contrast to the greatly increased power demand with smaller cut of the larger fir mill.

Attempts have been made to produce some sort of load equalizer, but only for some individual machines. The fluctuations are not at all regular; they might last for prolonged periods,

or might come in quick succession during one or two hours of operation, and might be very infrequent at other times. The demand question must be solved by those desiring to obtain the sawmill load, for its character is to a certain extent fixed.

In the case of the edger there is a machine with no flywheel effect whatever, a simple arbor with five to seven or eight saws, and it is operated by a motor of large capacity. Its highest load comes on instantaneously just as soon as the cant is started through the edger and it lasts until the cant has finished its travel and the cut has been made, seven to ten seconds. Those saws operate at a rim speed of 9000 to 12,000 ft. per min. and at speeds of 1200 to 1800 rev. per min. Any weight that could be added on the shaft of the edger would have to be of such small diameter and great length, to be within the safe limits of even the strongest materials, that it would run the cost up to too large an amount and take up too much space.

These loads are and have been well appreciated by sawmill operators. The operator lays out his plant to care for them. He knows the capacity plant required to care for the load, and in reality the effect of these fluctuations is not to increase the capacity of the equipment which it is necessary for him to have if he is going to generate his own power, and if they do not increase his own capacity why should he spend money to make it a more favorable market for the central station man? That is also the reason why efforts have not been made to obtain a better power factor. Of course it could be obtained, could be done by installing synchronous machinery.

The generating station—isolated or not—must for such a load have an automatic voltage regulator system, or they cannot expect to accomplish the results which they had anticipated with the electric drive. In operating at say 480 volts at the generator, which is a common voltage, it is exceptional to see the voltage drop below 460. Even with the severest load, such as the starting of the band headsaw, or the edger motor, there is a voltage drop, but it is instantaneous, the voltage going right back to normal again, and under running conditions you very seldom see a fluctuation of the voltage greater than one or two per cent at the outside.

In regard to the use of the refuse for briquets and turpentine, I referred on page 1353 to the experimental use of briquets for paving purposes: "Attempts have been made to use sawdust from Pacific coast mills, which cut mostly fir, spruce, and hemlock, for manufacturing wood alcohol and ethyl alcohol. In practise, however, the manufacturing costs run so high that it has proved unprofitable. The latest projected use is in making sawdust briquets to be used for paving purposes. Such a plant has been completed, although its operations have not extended over a sufficient period to determine the ultimate success." There have been several such attempts made, none of which has proved successful up to the present time, so far as I know.

It would be well to compare the use of the refuse for fuel for a steam generating station, in connection with a large power system, with the development of remotely located water powers. That would open up a field for power installations for the power company which in some cases they could not expect to get otherwise, because of the equipment already installed by the milling company.

I have heard some mention of the electrical drying scheme spoken of by Mr. Weber. I believe that was touched on briefly in *The Timberman* about two months ago. I have heard no comments on its real success.

An interesting feature of the mill spoken of by Mr. Harisberger is that it was the first case of which we have record where the headsaw was direct-connected to a driving motor. They had a double circular headsaw in this particular mill, the lower saw connected directly to the motor and the top saw belted from the lower one; the operation was entirely satisfactory—in fact, it is to be recommended, with proper precautions taken. The log carriage also was driven by a motor. I do not know the particular scheme that was used, but it was not entirely successful from the point of view of sawmill operation, because it did hold back production. Mr. Harisberger said that none of the Everett sawmills is completely operated from central station power. There are two completely electrically operated mills in Everett, however, with a third, the largest on the coast, under construction.

Presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Spokane, Wash., September 10, 1914.

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THE ELECTRICAL OPERATION OF THE BUTTE, ANACONDA & PACIFIC RAILWAY

BY J. B. COX

ABSTRACT OF PAPER

Of a total of ten notable instances of steam railway electrification in this country, the Butte, Anaconda & Pacific was the first if not the only one in which the prime cause for the change in motive power was an expected decrease in operating expenses sufficient to give immediately a satisfactory earning on the new investment of capital required for the improvement.

The preliminary investigations and estimates had indicated a probable annual saving amounting to about 17.5 per cent on the total investment, of which 11 per cent was expected to result from the partial substitution of electrical energy, costing about 0.552 cent per kw-hr. at the secondaries of the substation transformers, for coal of 12,250 B.t.u. calorific value and costing $4.25 per ton delivered. The remaining 6.5 per cent was expected from reduced cost of locomotive maintenance, engine house expense and enginemen's wages.

On this prospect, an expenditure of $1,201,000 was made in the electrification of 90 miles of track and in replacing 22 steam locomotives by 17 electric locomotive units which now operate about 80 per cent of the total locomotive-miles.

The actual results as indicated by the first six months of full electrical operation show the total net saving in operating expense to be at the rate of $242,299.12 per year or an earning of 20.02 per cent on the investment, of which the decrease in the cost of coal and power is 12.5 per cent.

Other savings are due to decreased cost of locomotive maintenance, engine house expenses, lubricants, supplies and trainmen's wages.

The average tons per train hauled by the electric locomotives has increased 33 per cent, the average time per trip decreased 30 per cent, the delays to traffic decreased 41 per cent, the number of trains decreased 25 per cent and the number of engine and train crews decreased 25 per cent.

THE AUTHOR wishes, at the outset, gratefully to acknowledge the assistance of Mr. H. A. Gallwey, general manager, Butte, Anaconda & Pacific Railway Company. It is through his coöperation and effort that the operating data given herein are made available. Information of this character has seldom been published and that it is here given to the public is a tribute to the broad-minded policy of the railway company.

The Butte, Anaconda & Pacific Railway was built in 1892

principally for the purpose of conveying the ore from the mines at Butte to the Washoe smelter which had been located at Anaconda, 26 miles west of Butte, where an abundant supply of water, so necessary in the reduction of the ore, was obtainable. The tracks connecting Butte and Anaconda constitute the main line, which is approximately 25.7 miles in length. As the mines are mostly around the top of Butte Hill and the shafts through which the ore is hoisted to the surface are scattered over a considerable area, yards were built at a convenient point on Butte Hill for the concentration of the cars containing the ore from these shafts, as well as to serve as a distribution point for the supplies to the mines, and a branch locally known as the Missoula

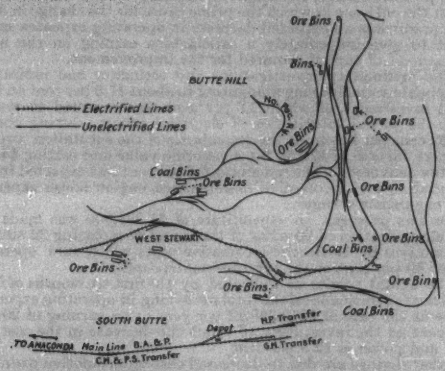


FIG. 2—OUTLINE MAP OF RAILWAY LINES ON BUTTE HILL FOR COLLECTION OF ORE AND DELIVERY OF SUPPLIES

Gulch line, Fig. 3, was built from these yards to connect with the main line at Rocker, where yards were also established.

Since the concentrator at the smelter is also on a hill at an elevation of approximately 340 ft. above the main line, it was advisable to establish another yard at East Anaconda from which to distribute the ore and other supplies to the different centers on Smelter Hill. The lines from these yards at East Anaconda to the smelter are known as the Smelter Hill lines, the longest branch of which is that leading to the concentrator, which is about 7¼ miles in length. Two spurs lead off from this main track, one to the stock bin yards and the other to the copper tracks, Fig. 4.

5400.00 above Sea Level
Elec. Ry.
3rd St. Elec. Ry.
Elec. Ry.
Foundry Tracks
To Smelter
Smelter Line
ANACONDA 25.00
SMELTERS 23.77
SILICA 21.93
STATION 21.03
Br. 21.56
Br. 21.35
To Smelter Crossing
Anaconda Yard
Montana Union
To Stuart
East Anaconda Yard
To Butte
To Smelter
Station
3rd St. Elec. Ry.
Elec. Ry. To Smelter
Silica

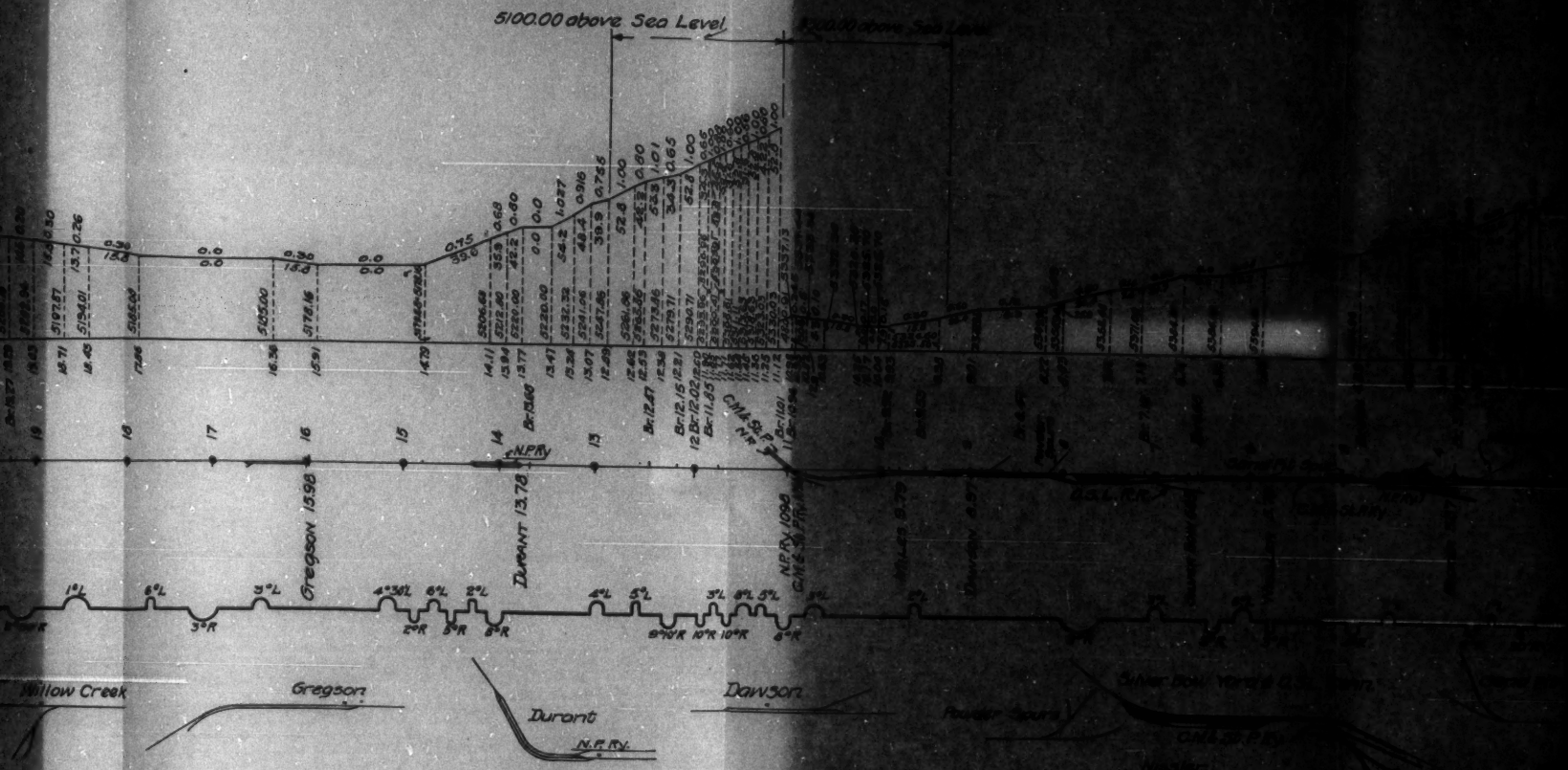


FIG. 1—BUTTE, ANACONDA & PACIFIC RAILWAY—CHART PROFILE, BUTTE TO ANACONDA
Horizontal Scale, 2 in. = 1 mile Vertical scale, 1 in. = 50 ft.

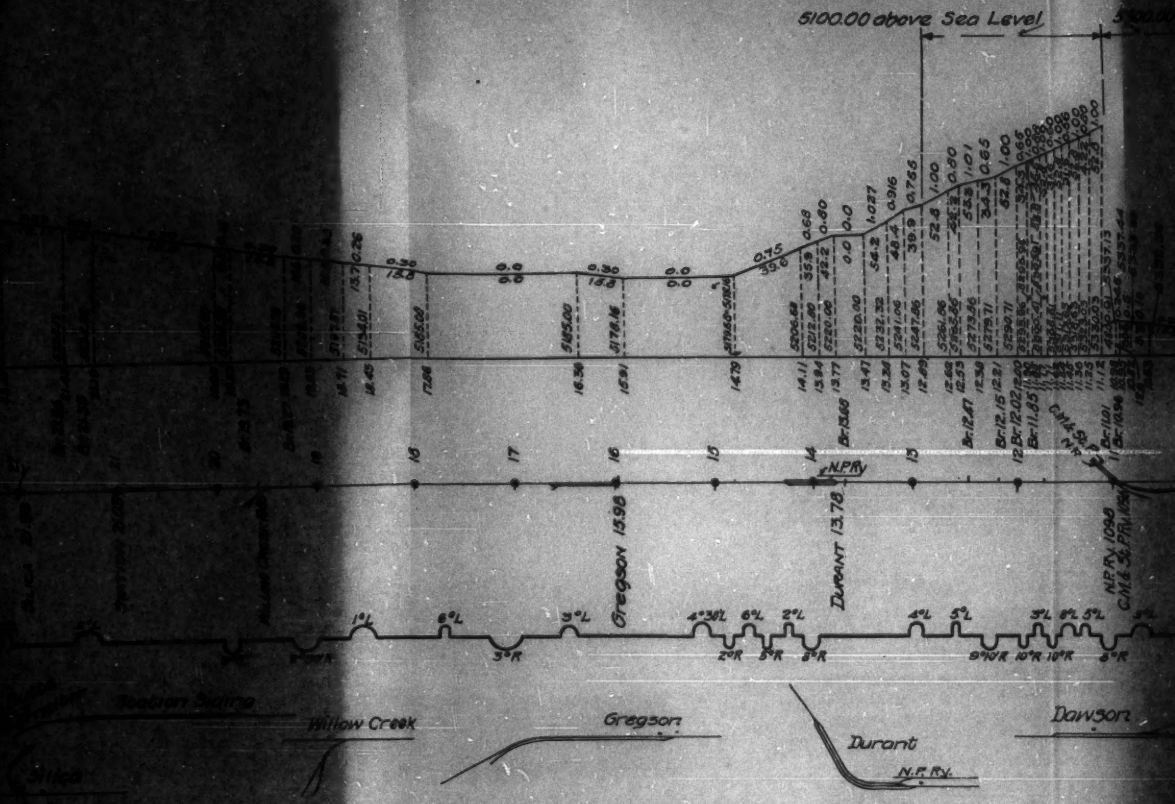
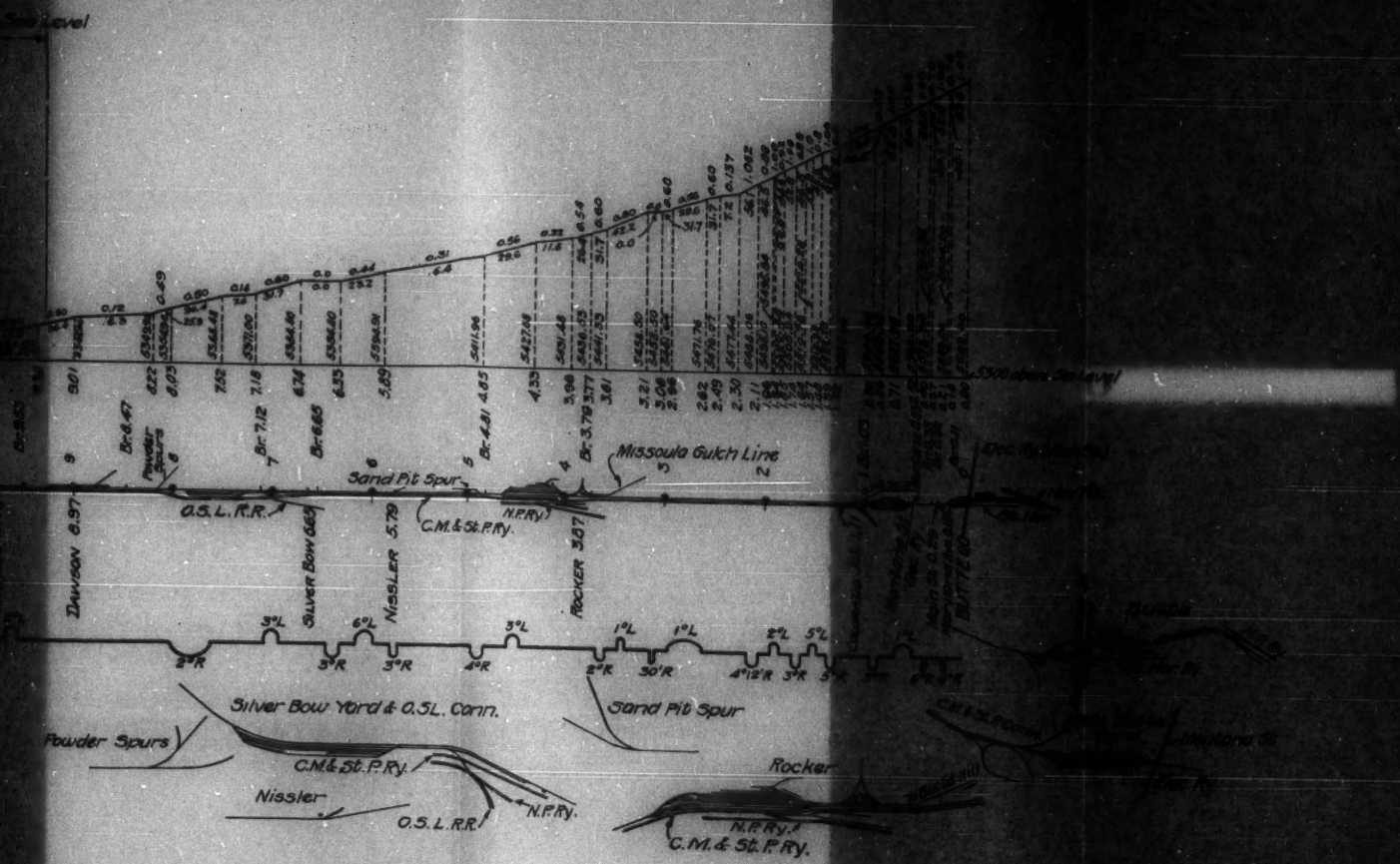


FIG. 1—BUTTE, ANACONDA & PACIFIC RAILWAY—CHART PROFILE, BUTTE TO A
Horizontal Scale, 2 in. = 1 mile Vertical scale, 1 in. = 50 ft.


Sea Level
5300 above Sea Level
Missoula Gulch Line
Sand Pit Spur
O.S.L.R.R.
C.M.& St.P.Ry.
N.P.Ry.
Powder Spurs
Br. 6.47
Br. 7.12
Br. 6.65
Br. 4.81
Br. 3.79
Dawson 8.97
Silver Bow 6.65
Nissler 5.79
Rocker 3.97
Silver Bow Yard & O.S.L. Conn.
Sand Pit Spur
Powder Spurs
C.M.& St.P.Ry.
Nissler
O.S.L.R.R.
N.P.Ry.
Rocker
N.P.Ry.
C.M.& St.P.Ry.

From the Butte Hill yards spur tracks radiate about Butte Hill to the shafts of the various mines and other points where supplies are to be delivered, Fig. 2. Bins for receiving ore as it is hoisted from the mines are located near each shaft and from these bins the ore is loaded into hopper-bottom steel ore cars of 50 tons capacity each, these loaded cars being delivered to the Butte Hill yards, where they are made up into trains and taken down to the Rocker yards, where they are made up into still larger trains and taken over the main line to East Anaconda yards. Here the trains are broken up to be transported in smaller units up Smelter Hill to the concentrator yards. Thus practically all of the ore cars are handled by five different engine crews between the ore bins at the mines and the receiving bins at the concentrator.

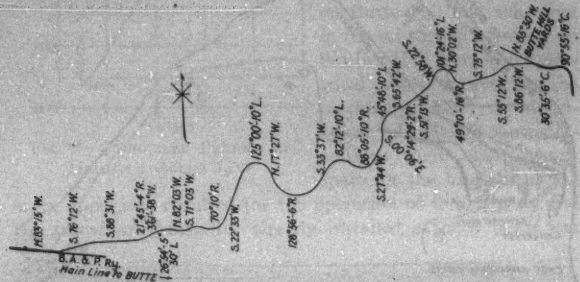


FIG. 3—MAP OF MISSOULA GULCH LINES, ROCKER TO BUTTE HILL YARDS, BUTTE, ANACONDA AND PACIFIC RAILWAY

A total of 27 steam locomotives was owned by the railway company, classified as follows:

Switching	7
Consolidation	8
Mastodon	10
Passenger	2

The coal used on the steam locomotives was obtained from the mines at Diamondville, Wyoming, and had to be transported approximately 395 miles for delivery to the bins of the railway company, at which point its average cost was approximately $4.25 per ton.

The machinery at the mines and the smelter had mostly been electrified, and the results had been so satisfactory that the

railway company had a study of their conditions made for the purpose of investigating the advantages that might be expected from the electrification of their lines, the result of which was the placing of a contract in December, 1911, for the electrical equipment of the main portion of its line, consisting of the main line, spurs and yards between Butte and Anaconda, the Missoula Gulch line between Rocker and Butte Hill yards and the Smelter Hill lines. Owing to local conditions on the spur tracks leading to the various mines from Butte Hill yards, it was thought advisable not to electrify these until a later date.

Three of the steam switching locomotives listed above were

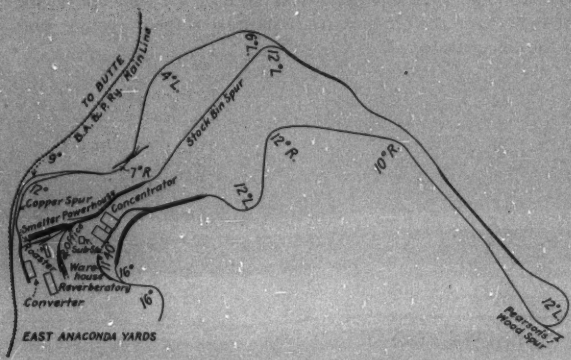


FIG. 4—MAP OF SMELTER HILL LINES, BUTTE, ANACONDA AND PACIFIC RAILWAY

used daily on Butte Hill collecting ore from and delivering supplies to the various mines from the Butte Hill yards.

The Georgetown extension to Southern Cross, 22.9 miles west of Anaconda, was underway at the time, but as it was expected that a few trains per week would take care of the traffic over this branch for some time, its electrification was not seriously considered in the original study.

It is fair to assume that a vital consideration leading to the electrification of this railroad was the rapid development and physical consolidation of a network of hydroelectric power plants in the territory tributary to the railroad.

A contract for the power for the operation of the road was made with the Great Falls Power Company, which, operating under

the same management and in physical connection with the system of the Montana Power Company, was enabled to guarantee an ample supply of power at all times with exceptional freedom from interruptions to service, and at a reasonably low price.

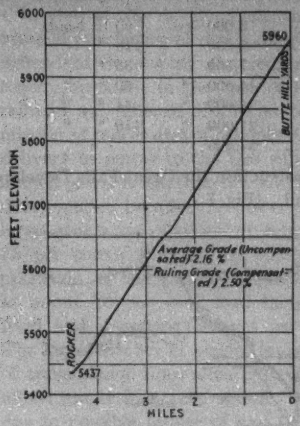


FIG. 5—CONDENSED PROFILE OF MISSOULA GULCH LINE

The tracks recommended to be electrified totaled approximately 90.5 miles, all of which are supplied with power from two substations, one being located in the Missouri River Power Company substation on Butte Hill and the other in the substation building on Smelter Hill, from which electrical power for operating the machinery there is distributed. At each of these substations there was vacant space for the location of the extra apparatus required for the operation of the railway, and the transformer capacity already installed at each place was

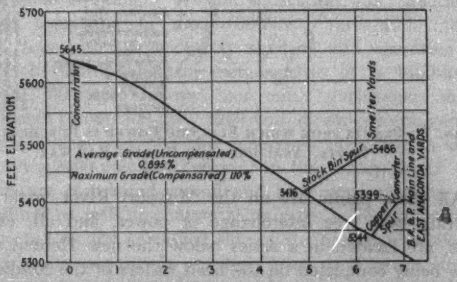


FIG. 6—CONDENSED PROFILE OF SMELTER HILL LINES

sufficient to meet the extra demand required for the operation of the railway.

The Anaconda substation is connected with the Butte substation by three high-tension trunk lines. The Butte substation

receives power over five separate transmission lines from six hydroelectric stations of the following rated capacities:

Big Hole Development	.....	3,000 kw.	60 ft. head.	
Madison River "	.....	9,000 "	110 "	"
Canyon Ferry "	.....	7,500 "	35 "	"
Hauser Lake "	.....	14,000 "	60 "	"
Black Eagle "	.....	3,000 "	44 "	"
Rainbow "	.....	21,000 "	110 "	"
Total	.....	57,500 "		

There is also now under construction the Great Falls Development, 60,000 kw., 155-ft. head. (Fig. 7.)

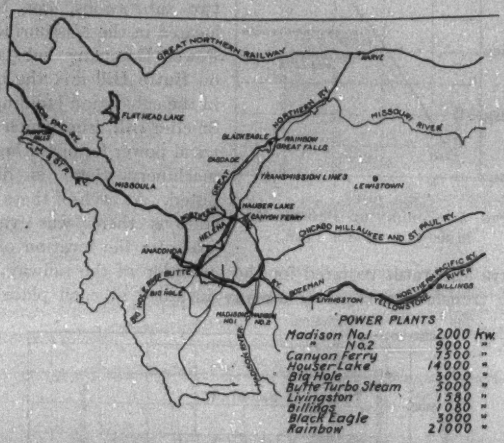


FIG. 7—PLANTS FROM WHICH ELECTRIC POWER IS PURCHASED BY THE BUTTE, ANACONDA AND PACIFIC RAILWAY.

All these plants are on the Missouri River water shed, all operate with free interchange of power, and all, except the first, are located in a series below the new Hebten reservoir, now being completed on the head waters of the Madison river, with an available capacity of 300,000 acre-ft. of storage.

The individual plants are also provided with storage reservoirs aggregating 125,000 acre-feet of total available storage capacity. All of these reservoirs operating under one control are capable of developing from stored water alone, in addition to the power otherwise available from the natural flow of the river, the

equivalent of about 100,000 electrical horse power for a period of 100 days.

In view of this development, the generally recognized advantages of purchasing electric power from a large operating system instead of developing the required power independently were readily apparent in the case of the B. A. & P. railway. The railroad was relieved of all first cost of development and transmission of power and of all operating expense up to the point of delivery of power to the two substations. The cost of the delivered power is less than it would have been from an independent development, because the power company is enabled to operate large generating stations at relatively high load factor (about 75 per cent), whereas an independent plant purely for the operation of the railway would have to operate in this case at about 30 per cent load factor, with correspondingly high fixed and operating charges per kilowatt-hour actually used. The large number of generating stations and complete network of transmission lines already developed by the power company afford ample insurance against interruption to railroad service due to possible failure of any part of the generating or transmitting system of the power company, and the enormous inertia or flywheel effect of the motor loads connected to the power system maintain extremely steady speed and voltage under the most extreme variations of load on the railroad.

The original equipment of each substation was practically the same, consisting of two 1000-kw., three-unit motor-generator sets with the necessary starting and operating devices. Each motor-generator set consists of a 1450-kv-a., three-phase, 60-cycle, 720-rev. per min. synchronous motor coupled direct to two 500-kw., 1200-volt direct-current generators, one at either end, the two generators operating in series and supplying 2400-volt direct current to the trolley lines. The generators are compound-wound and have compensating pole face windings as well as commutating poles. The series fields are connected on the grounded side of the armature, while the main fields are separately excited from a 125-volt circuit. The motor-generator sets are capable of carrying overloads up to three times normal load momentarily, and 50 per cent overload for two hours. The value of this characteristic will be appreciated when it is noted that each electric locomotive unit has a continuous rating of approximately 900 kw., almost equal to that of a single motor-generator set, and frequently 16 of the

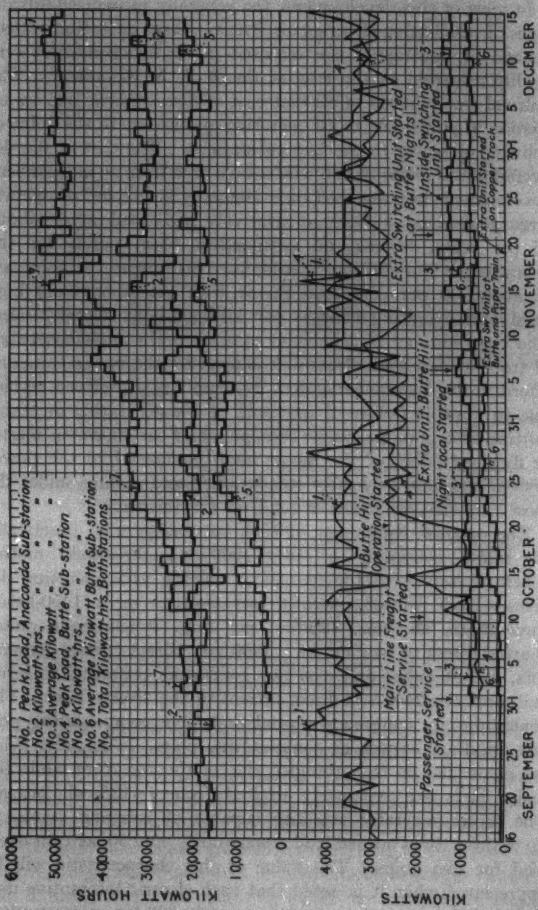


FIG. 8—DIAGRAM SHOWING SUBSTATION LOADS

FIG. 9—EIGHTY-TON, 2400-VOLT LOCOMOTIVE [COX]

FIG. 10—TYPE OF STEAM SWITCHING LOCOMOTIVE FORMERLY USED ON BUTTE HILL [COX]

FIG. 11—2400-VOLT MOTOR-GENERATOR SET CONSISTING OF ONE 1450-KV.A., 2300-VOLT 60-CYCLE SYNCHRONOUS MOTOR AND TWO 500-KW., 1200-VOLT, D-C. GENERATORS IN SERIES

17 units are in service simultaneously, 11 of which are concentrated at the Anaconda end at intervals.

Seventeen 80-ton electric locomotive units were purchased, originally, fifteen of which are being operated in freight service and two in the passenger service. These units are practically interchangeable, with the exception of the gearing, the passenger locomotive being geared to operate normally at 40 or 50 mi. per hr. while the freight locomotives are geared to operate at from 15 to 25 mi. per hr., the maximum free running speed being approximately 35 mi. per hr. The continuous tractive

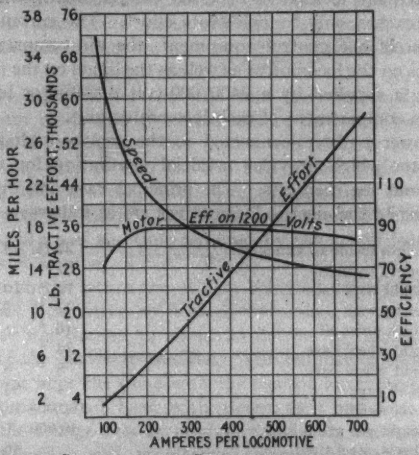


FIG. 12—CHARACTERISTIC CURVES OF FREIGHT LOCOMOTIVES

effort of the freight units is 25,000 lb., at 15 mi. per hr., but they are capable of exerting a maximum tractive effort of 48,000 lb. for five-minute intervals, based on a coefficient of adhesion of 30 per cent.

All the locomotive units are of the articulated, double-truck type with twin gears mounted on projections provided on the wheel centers for the purpose, and in general mechanical design are similar to the electric locomotives in operation on the Great Northern railway, the Detroit River Tunnel railway and the Baltimore & Ohio railway. Each unit is equipped with four commutating-pole motors wound to operate at 1200 volts each,

but insulated for 2400 volts, so that two are connected permanently in series and the four arranged in pairs, thus securing the usual two running points, with the difference that on the series position all four motors are in series, and in multiple the two pairs are connected in series-parallel.

The standard rating of each motor is approximately 300 h.p., making the hourly rating of each locomotive unit about 1200 h.p. The control equipment is of the multiple-unit type and provides a total of 19 steps, ten of which are in series and nine in series-parallel. The 2400-volt contactors, switches, fuses, etc., are located in enclosed compartments where they can be reached only by deliberate effort. The current for the operation of the control equipment, the air compressor, and the lights on the locomotive as well as the lights on the passenger coaches, is supplied by a 2400/600-volt dynamotor located in the main compartment of each locomotive unit.

A blower is direct-connected to the armature shaft of this dynamotor which provides artificial ventilation for the main motors and the rheostats. The principal data and dimensions pertaining to the electric locomotives are as follows:

Length inside of knuckles	37 ft.	4 in.
Length over cab	31 "	
Height over cab	12 "	10 "
Height with trolley down	15 "	6 "
Width over-all	10 "	
Total wheel base	26 "	
Rigid wheel base	8 "	8 "
Track gage	4 "	8½ "
Total weight	160,000 lb.	
Weight per axle	40,000 "	
Wheels, steel tired		46 "
Journals	6 "	13 "
Gears, forged rims, freight locomotives	87 teeth.	
Gears, forged rims, passenger locomotives	80 "	
Pinions, forged, passenger locomotives	18 "	
Pinions, forged, freight locomotives	25 "	
Tractive effort at 30 per cent coefficient	48,000 lb.	
Tractive effort at one hour rating	30,000 "	
Tractive effort at continuous rating	25,000 "	

Work on the electrification began in the spring of 1912, and the first electric locomotive was run in Anaconda on May 14th, 1913, about a year later.

On May 27, two ore trains were hauled up Smelter Hill on trial trips with electric locomotives and on the following

day a double-unit electric locomotive took over the regular day service of hauling the ore from East Anaconda yards to the concentrator yards, the distance between which is approximately seven miles, the ruling gradient being 1.1 per cent compensated, and the grade fairly uniform through the entire distance, Fig. 6. The steam locomotives used in this service were of the Mastodon type, weighing 108 tons, 83 tons of which was on the drivers. The weight of the tender loaded was approximately 55 tons, making the total weight of locomotive and tender about 163 tons, which would average closely to the weight of the double-unit electric locomotive superseding it. The steam locomotive made ordinarily six round trips per shift, hauling 16 loaded ore cars per trip, equaling 96 cars per shift.

The average time for the trip from East Anaconda to the concentrator yards with 16 loaded cars for the steam locomotive was about 45 minutes. The double-unit electric locomotive began taking only 16 cars per trip but made 8 trips per shift, delivering 128 cars per shift. The average time for the up-hill trip with the electric locomotive was about 22 minutes, or approximately half the time required by the steam locomotive for the same number of cars. Empty cars were taken to East Anaconda on the return trip which, being all down grade, gave the electric locomotive no decided advantage, as the speed in either case was limited to about 25 mi. per hr. for safety, on account of the curves in the line. The number of cars hauled per trip was kept the same with the electric locomotives in the beginning as it had been with steam, as it had been decided to make the change-over by gradually replacing one steam locomotive at a time with an electric, taking the engine crew off the one and placing it on the other, thus breaking them in on the electric locomotives in regular service.

One of the regular steam engineers had been given special instructions on the electric locomotives during the experimental running in order that he might become competent to act as instructor to the other engineers until they were sufficiently familiar with the electric locomotives to be left alone.

The load per trip in this service was gradually increased from 16 cars to 25 cars, which is to be the standard for the present. The average time for the up-hill trip with 25 cars is about 26 minutes so that eight trips per shift are easily made, making a delivery of 200 cars possible or an increase of slightly more

than 108 per cent over what had been possible for the same crew with steam locomotives. These loaded ore cars average from 70 to 72 tons each, making the trailing load for a 25-car train from 1750 to 1800 tons.

On arrival at the concentrator yards the ore trains are taken by a switching engine called the "spotter", which places one car at a time over the weighing scales, after which they are rearranged for placement over the concentrator bins from which the ore is fed by gravity to the crushers.

On June 20th this spotting service was taken over by a single-unit electric locomotive and on July 2nd the night service up Smelter Hill was taken over by the double-unit electric locomotive. The steam locomotive used for the spotting service was of the consolidation type and weighed 93 tons, 83 of which was on drivers, the tender weighing loaded 62 tons, making the total weight of engine and tender 155 tons. The steam locomotive used in the night service on Smelter Hill was similar to that used in the day service. When the electric engines were put on the night service all the handling of ore between East Anaconda and the concentrators was done electrically, and the hauling capacity per crew was so much greater that it was no longer necessary to have a "spotter" crew on the night shift so that this crew was eliminated, and the night crew hauling the ore up Smelter Hill did their own spotting on arrival at the concentrator yards, it being no longer necessary to make the regular number of trips. Thus, where formerly during steam operation four engine and train crews had been required, now with electric locomotives three similar crews were able to do the same work and in less time, thereby reducing the number of crews required in this particular service 25 per cent.

On July 9th the stock bin engine was replaced by an electric unit. This engine is engaged mostly in a switching service, placing cars of coke, coal and other supplies at the smelter. The type of steam engine used here was the same as that used for the "spotter" service described above.

Another engine locally known as the "tramp" because of the irregularity of the time or place of its service was partially replaced on July 24th. As some of the tracks over which this engine had to operate at times had not been equipped with overhead wires, the infrequency of their use not warranting the expense when other conditions made it necessary to keep one or more steam locomotives in operation, the service of this

FIG. 13—BRACKET TANGENT CONSTRUCTION ON SMELTER HILL [COX]

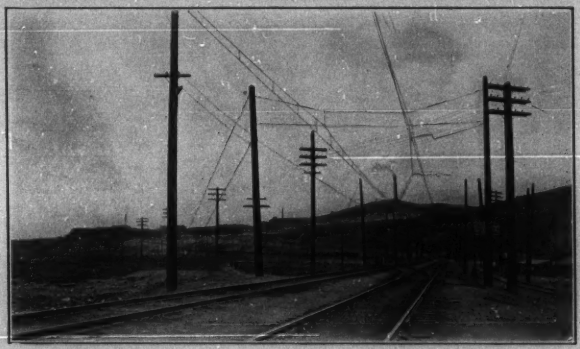


FIG. 14—DOUBLE TRACK SPAN CONSTRUCTION ON MAIN LINE AND GENERAL VIEW OF SMELTER HILL FROM WEST OF EAST ANACONDA YARDS

FIG. 15—STORAGE BINS AT CONCENTRATOR [COX]

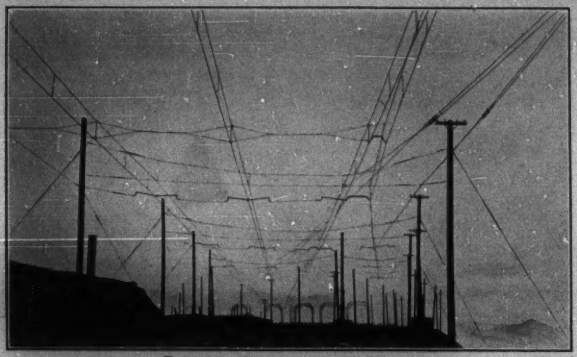


FIG. 16—CONCENTRATOR YARDS [COX]

FIG. 17—OVERHEAD CONSTRUCTION IN ROCKER YARDS [COX]

FIG. 18—SIXTY-FIVE CAR ORE TRAIN--TOTAL TRAILING LOAD 4550 TONS [COX]

electric unit was intermittent. This practically completed the electrification of the Smelter Hill service and no further extension of electrical operation was made until October, as the trolley construction on the main line was not completed until that date.

On the forenoon of Sept. 30th an inspection trip was made over the main line from Anaconda to Butte and in the afternoon a special train carrying officials and visitors from a neighboring road was taken from Butte to Anaconda and return by one of the electric locomotives intended for the passenger service. On October 1st the regular passenger service between Butte and Anaconda was taken over for electrical operation. The steam locomotives used in the passenger service weigh approximately 80 tons, 60 tons of which are on drivers, the tender loaded weighing 52 tons, making the total weight of engine and tender 132 tons. The distance between the stations—Anaconda to Butte—is 25.7 miles, the schedule time for the trip, one hour. No change has been made in this time, though a reduction of 20 per cent would be possible with the electric locomotives were such desired. The standard passenger train consists of one mail and baggage coach and two to four passenger coaches, but as many as 12 passenger coaches are handled by a single electric unit on special occasions, such as excursions and on holidays.

The baggage coaches average approximately 40 tons in weight and the passenger coaches 45 tons each making, the gross weight of the three-car electric train approximately 210 tons, whereas that of a similar steam train was 262 tons, showing a reduction of 19 per cent in favor of the electric locomotive with approximately 33 per cent more weight on its drivers. As had been done in the freight service, the steam enginemen in the passenger service were transferred from the steam to the electric locomotives with but little previous instruction, and after the first day or so were left mostly to themselves. It may be of interest to note here that on the day shift, averaging four trips per day, during the first five months the passenger train did not come in late a single time on account of engine trouble. A comparison of the delays to the passenger trains for the month of June, 1913, steam operation, with the same month, electrical operation, 1914, as shown in Table V, results as follows:

	No. of Trains	Delays on Account of				Total Delays
		Meeting Points	Power	Engine Failure	Lost Run Time	All Causes
		Hr. Min.	Hr. Min.	Hr. Min.	Hr. Min.	Hr. Min.
Steam, 1913	272	16 : 49		44	4 : 13	20 : 46
Elec., 1914	280	3 : 54	27	24	25	5 : 10
Decrease	8*	11 : 55	27*	20	3 : 48	15 : 36
Percentage of saving due to electrical operation	2.94*	75.66		45.45	90.10	75.12

* Increase.

June was taken at random for a comparison, as that month's records were still in the office file but the results are considered representative of general performances.

On October 10th a double-unit electric locomotive was put in the day freight service on the main line between East Anaconda and Rocker, a distance of 20.1 miles. The steam locomotive replaced in this instance was of the Mastodon type weighing 103 tons, 77 tons of which was on drivers, the tender loaded weighing 55 tons, making the total weight of locomotive with tender 158 tons. The standard train hauled on the trip west was 50 to 55 loaded ore cars weighing approximately 3500 to 4000 tons gross and the average running time of such trains where no stops were made was about 1½ hours, corresponding to an average speed of approximately 13.4 miles per hour. In the beginning the electric locomotive took only the standard train but made the trip without stop in about one hour, corresponding to an average speed of 20 mi. per hr. The ruling gradient on the westward trip is 0.3 per cent and about half the distance is down grade. On the 0.3 per cent grade with a 55-car train, the steam locomotive made about seven mi. per hr. The electric locomotives with similar train now make about 16 mi. per hr. on the same grade.

The weight of the trains hauled by the electric locomotives on this run has been gradually increased up to 65 loaded ore cars averaging about 71 tons each, making the gross weight

trailing about 4620 tons. Adding 160 tons for the weight of the double-unit electric locomotives and 20 tons for the caboose makes a gross train weight of approximately 4800 tons.

The remainder of this main line freight service was gradually taken on during the months of October and November, thus completing the electrification of the main line service. As many as 76 ordinary freight cars loaded with coal, coke and general merchandise have been taken in a single train on the west-bound trip and 85 empties are frequently taken from East Anaconda to Rocker east-bound, the ruling grade being one per cent.

Table IV gives comparative results of the month of June 1913 steam operation vs. the same month, 1914, electrical operation of this main line service, showing that with a slight increase in the total tons of ore hauled the average tons per train was increased from 1761 to 2378 or 35 per cent, thus decreasing the average number of trains per day from 12.5 to 9.3, or 25.6 per cent.

Table III, giving a comparison of the time per trip for these trains, is representative of the gain in this direction to be added to the decrease in the number of trains. The average time per trip during steam operation was approximately two hours and 25 minutes, while with the electric locomotive it was approximately one hour and 45 minutes, showing a decrease of 40 minutes, or 27.5 per cent. These figures represent the time put in by the crews between Rocker and Anaconda, the distance being 21.8 miles.

The result of these improvements is indicated in Tables I and II, which show that the overtime in this particular service has been decreased 73.5 per cent and the total time 42 per cent, resulting not only in greater economy to the railway company but in shorter and easier hours for the crews.

The service on the Missoula Gulch line running between Rocker and Butte Hill yards was taken over for electrical operation on October 20th. This line is 4.5 miles in length and the ruling gradient 2.5 per cent, Fig. 5. The steam locomotives used on this line were of the Mastodon type, weight 106 tons, 87 tons of which were on the drivers, the tender loaded weighing 56 tons, thus making the total weight of engine and tender 162 tons. Two complete crews had been required to handle this service during steam operation, averaging six trips per day each. A single crew with a double-unit electric locomotive has

been doing this work successfully. Thirty-five to 45 loaded ore cars are taken down from Butte Hill yard to Rocker, and about an equal number of empties taken up. In addition to the empties, large quantities of timber and supplies for the mines are delivered over this line.

TABLE I

NUMBER OF HOURS ENGINE CREWS WERE EMPLOYED IN VARIOUS SERVICES—JUNE 1913 STEAM OPERATION

Date	Anaconda Yard		Butte Hill Yard		Local		Road	
	Regular	Over	Regular	Over	Regular	Over	Regular	Over
	Time Hr.	Time Hr.	Time Hr.	Time Hr.	Time Hr.	Time Hr.	Time Hr.	Time Hr.
June 1	80	14	20	4.50	20	3.25	30	13.75
2	90	6.50	20	6.50	20	5.75	40	17.25
3	50	5	—	—	20	5.25	40	15
4	70	11.75	20	8.25	20	6.75	30	11.50
5	80	11.75	20	8.00	20	6.00	30	12.25
6	70	9.25	20	9.00	20	10.00	30	14.50
7	80	13.75	20	8.75	20	6.50	30	11.25
8	70	8.00	20	8.75	20	4.75	30	12.25
9	70	10.50	20	11.50	20	8.25	30	11.50
10	80	8.75	20	7.75	20	2.00	30	9.00
11	80	13.	20	10.25	20	7.00	30	10.50
12	70	7.00	20	2.00	20	5.25	30	12.00
13	40	5.25			10	1.00	20	6.75
14	70	12.25	20	11.25	20	7.50	30	9.50
15	70	10.25	20	8.75	20	5.25	30	11.00
16	80	8.75	20	9.75	20	16.00	30	9.25
17	80	7.75	20	9.00	30	11.00	30	15.25
18	70	12.25	20	7.50	20	10.75	30	12.50
19	70	9.50	20	9.00	20	3.75	30	8.00
20	80	12.00	30	10.75	20	5.75	30	8.75
21	80	9.75	20	10.25	20	3.50	30	12.75
22	70	5.50	20	7.75	20	5.75	30	10.00
23	70	7.00	20	8.25	20	6.75	30	8.75
24	80	7.50	20	4.50	20	8.00	30	9.00
25	70	9.25	20	6.00	20	9.00	30	11.50
26	80	10.25	20	9.00	20	7.00	30	13.27
27	70	7.75	20	7.50	20	7.00	30	10.25
28	70	5.50	20	2.50	20	4.75	30	9.00
29	80	6.00	20	1.50	20	3.75	30	9.75
30	80	8.75	20		20	7.00	30	9.50
Total	2200	274.50	570	208.50	600	194.25	910	335.50

Tons Ore Hauled During Month—311,450.

On November 25th, the last of the electric locomotive units went into service, thus completing the electrification originally intended. The full electrical service has, therefore, now been in operation more than nine months and that on Smelter Hill

more than 15 months, so that the total locomotive-miles operated would be approximately close to an average year's performance.

TABLE II

NUMBER OF HOURS ENGINE CREWS WERE EMPLOYED IN VARIOUS SERVICES—JUNE 1914 ELECTRICAL OPERATION

	Anaconda Yard		Butte Hill Yard		Local		Road	
Date	Regular Time	Over Time	Regular Time	Over Time	Regular Time	Over Time	Regular Time	Over Time
June 1	70	7.25	20	1.25	20	2.50	30	2.25
2	70	8.25	20	4.00	20	2.50	30	5.00
3	70	9.50	10	1.00	20	4.00	30	1.25
4	60	7.25	10	2.00	20	2.75	30	4.25
5	60	12.50	10	2.00	20	2.75	20	2.50
6	60	7.25	10	2.00	20	2.50	20	2.25
7	70	8.25	10	2.00	20	2.00	20	6.25
8	60	8.75	10	1.75	20	2.75	20	3.00
9	60	10.50	10	1.50	20	4.75	20	4.75
10	60	11.25	10	1.75	10	1.00	20	1.75
11	60	5.00	10	1.50	20	3.75	20	1.25
12	60	9.00	10	1.00	20	2.00	20	1.25
13	30	1.75	10	1.00	10	1.00	10	4.00
14	60	5.50	10	1.25	20	2.25	20	1.25
15	60	6.50	10	1.00	20	2.75	20	1.50
16	60	4.00	10	1.50	20	2.50	20	2.00
17	60	7.75	10	1.00	20	3.00	20	2.75
18	60	8.75	10	1.75	20	2.25	20	1.50
19	60	7.25	10	3.00	20	2.25	20	2.25
20	60	10.75	10	1.75	20	2.25	20	5.75
21	60	8.75	10	1.75	20	2.25	20	1.25
22	50	5.50	10	1.00	20	2.75	20	2.25
23	60	6.75	10	1.00	10	1.50	20	3.50
24	60	11.25	10	1.50	20	3.00	20	3.50
25	60	7.75	10	1.50	20	2.25	20	5.25
26	60	5.75	10	1.25	20	2.50	20	1.75
27	60	8.50	10	1.25	20	2.00	20	3.75
28	60	4.25	10	3.00	10	1.75	20	2.00
29	60	6.00	10	1.00	10	1.75	20	5.50
30	60	10.50	10	1.25	20	2.25	20	3.50
Total	1800	232.00	320	48.50	550	73.50	630	89.00
Decrease	400	42.50	250	160.00	50	120.75	280	246.50

	Regular	Over	Total
Total time 1913—Steam	4280.00	1012.75	5292.75
" " 1914 Electric	3300.00	443.00	3743.00
Decrease	980.00	569.75	1549.75
Percentage of decrease	22.89%	56.26%	29.28%

Tons ore hauled during month—319,700

This was the first installation of 2400-volt direct-current apparatus for the operation of a railway in this country, 1500 volts being the highest heretofore installed for such a purpose.

The results have been more satisfactory than had been anticipated and the development charges due to such imperfections as usually appear during the first year of operation have been perhaps smaller than is customary with an undertaking of like magnitude, even where standard apparatus is used.

TABLE III

COMPARISON OF TIME REQUIRED PER TRIP OF FREIGHT TRAINS. BETWEEN ROCKER AND ANACONDA—FIRST 2 DAYS OF JUNE 1913, STEAM OPERATION, WITH CORRESPONDING 3 DAYS ELECTRICAL OPERATION.

	1913 Steam					1914 Electric			
	East Bound.			West Bound		East Bound		West Bound	
Train	No.	Tons	Time	Tons	Time	Tons	Time	Tons	Time
			Hr. Min.		Hr. Min.		Hr. Min.		Hr. Min.
	1	255	1 : 13	1705	2 : 00	380	1 : 02	2915	2 : 00
	2	1010	1 : 50	2848	2 : 05	314	1 : 15	3092	2 : 00
	3	1010	3 : 20	3760	2 : 10	1336	1 : 45	4088	1 : 20
1st	4	915	2 : 40	3420	2 : 30	1260	1 : 40	3830	1 : 10
	5	1047	2 : 30	2944	3 : 45	1240	1 : 40	4009	2 : 05
	6	1000	2 : 20	2935	2 : 05	..	..	..	..
	7	1010	4 : 00	..	..	..	..	..	..
	1	415	1 : 07	3110	3 : 40	416	1 : 10	3100	2 : 00
	2	1010	2 : 10	3760	2 : 10	1154	1 : 40	3220	1 : 25
2nd	3	1010	2 : 45	2884	2 : 00	1298	2 : 00	3752	2 : 20
	4	1010	3 : 00	3420	2 : 00	458	1 : 45	4029	2 : 10
	5	1104	2 : 20	3420	2 : 00	1232	2 : 00	3720	2 : 20
	6	1000	3 : 00	2910	2 : 50	1190	1 : 55	2840	2 : 35
	1	380	1 : 02	3380	2 : 50	470	1 : 03	2515	1 : 15
	2	1010	1 : 50	1630	2 : 45	1280	1 : 40	3964	1 : 10
3rd	3	992	2 : 50	200	2 : 00	1298	2 : 05	4098	1 : 30
	4	884	2 : 20	0	1 : 20	482	1 : 40	3760	1 : 40
	5	1046	2 : 40	3150	2 : 30	1074	2 : 10	3138	2 : 30
	6	1084	3 : 15	2770	2 : 40	1200	2 : 15	0	1 : 10
Totals	19	17192	46 : 12	18-48246	43 : 20	17-16082	28 : 45	17-56070	30 : 40
Av'ge per Train.....		905	2 : 26	2680	2 : 24	946	1 : 41	3298	1 : 48

Grand Average. 1768 tons per train, time per trip 2.25; 2150 tons per train, time per trip 1:45.

Result. 20.0% increase in tonnage per train, 27.58% decrease in time per trip.

*On June 5th, 1914, one main line crew was taken off and the tonnage of the remaining trains increased so as to handle the regular business.

Difficulties especially attributable to the higher potential have been negligible, and while there have been occasional instances of arcing and flashing or short circuits due to ordinary causes, the resultant damages have been really smaller than

might be expected from a like occurrence on a 600-volt installation of equal capacity.

The original brushes supplied in the motors chipped badly

TABLE IV

COMPARISON OF FREIGHT TRAIN MOVEMENTS BETWEEN ROCKER AND ANACONDA. STEAM OPERATION FOR MONTH OF JUNE 1913 WITH ELECTRICAL OPERATION FOR SAME MONTH 1914

	1913 Steam				1914 Electric			
	East Bound		West Bound		East Bound		West Bound	
Date	No. Trains	Total Tons	No. Trains	Total Tons	No. Trains	Total Tons	No. Trains	Total Tons
1	7	6247	6	17612	5	4530	5	17934
2	6	5549	6	19504	6	5748	6	20661
3	6	5396	6	11130	6	5804	6	17425
4	7	5584	6	14632	6	6127	6	18332
5	7	5848	6	14625	5	5334	5	17155
6	7	5877	6	19471	4	4804	4	17563
7	7	5698	6	21021	5	6579	5	19073
8	7	6388	7	17023	5	6083	5	14170
9	6	5508	7	12507	5	5796	4	15292
10	6	5039	6	19240	5	6027	5	16926
11	6	5381	5	15925	4	5345	4	12832
12	5	4376	6	18112	5	5670	5	17881
13	5	3705	5	9565	2	2322	1	3042
14	6	4912	6	7841	4	4638	4	13803
15	7	5652	7	17691	5	5262	4	15761
16	6	5180	7	17518	4	5116	4	16408
17	6	5475	6	16090	5	6433	5	20581
18	6	5483	6	16592	4	5141	4	17546
19	7	6003	6	18301	5	6661	5	18489
20	7	5277	6	22283	5	6768	5	17992
21	7	5737	6	18986	4	5120	4	11932
22	7	5082	6	15464	5	6017	5	15613
23	6	5386	6	11941	4	4121	4	15930
24	6	5098	6	18210	5	6556	5	18917
25	7	5544	7	17992	5	6531	5	16855
26	7	5690	6	18304	5	6782	5	18593
27	7	5935	6	14764	4	4362	4	18038
28	7	5754	5	17297	4	5047	4	14884
29	6	5105	6	19899	5	6455	5	17941
30	6	5221	6	17584	5	6617	5	18128
Total.....	193	163,130	182	497,124	141	167,796	138	495,697
Average....	6.4	345	6.1	2,731	4.7	1,190	4.6	3,592

Grand Average 12.5 trains per day, 1761 tons per train. 9.3 trains per day, 2378 tons per train.

Results—25.6% less trains. 35.0% greater tonnage per train.

and before all these had been replaced it was often found when the units were brought in for regular inspection that some of the brushes were broken entirely into pieces, and while there

was evidence that a flash-over might have occurred at some time, no harm had resulted other than the blowing of the motor fuse, on the replacement of which the engine was continued in service until its regular time for inspection, when the cause of the fuse blowing would first be discovered.

The fact that the locomotives continued in service thus is sufficient evidence of the harmlessness of the arc-over and in no instance of the kind has any real damage been done. The locomotives have made from 25,000 to 50,000 miles each and without exception the motors are in excellent condition. The wear on the commutators is imperceptible and the general performance of the entire equipment is quite as satisfactory and promising as that of any railway equipment with which we have had experience in similar service.

The overhead construction has been quite satisfactory and a recent examination of the trolley wire shows no indication of unusual wear. The roller pantographs are operating quite successfully, the average life of these being from 10,000 to 12,000 miles per roller. Where a double-unit locomotive is operated, the two pantographs are connected electrically by a main bus line, and the average current collected by each, when ascending the grades with standard loads, is from 350 to 400 amperes. Two pantographs operating in multiple thus will collect more than double the current that can be successfully collected by a single pantograph for the reason that sparking is usually due to the momentary breaking of contact between the trolley wire and the roller caused by hard spots in the line. When two pantographs are operated in multiple both do not encounter these hard spots at the same instant, hence one of the two is more apt always to be making good contact, so that the flow of current is not so frequently interrupted and consequently the sparking is greatly reduced. The double units operating on Smelter Hill were run experimentally for several days with only a single roller making contact with the wire, the operation being quite successful with the single roller collecting an average of 650 to 750 amperes while running at 16 to 17 mi. per hr. and 800 to 1000 amperes during the accelerating period in multiple. The sparking was not serious except at hard points in the line, and with two rollers in multiple there should be no difficulty in collecting 500 to 600 amperes per roller, which at 2400 volts should be equal to the requirements of any ordinary locomotive unit.

The bearings first used in the rollers were provided with ordinary bushings lubricated with oil but when the bushings became slightly worn the oil was thrown out along the spindle and had to be replenished at comparatively frequent intervals. This was not serious in the operation of the freight locomotives but became more so when the passenger service was started, as the higher speed caused the oil to be thrown out more quickly, resulting in very short life of the bushings. Slight changes were made in the bearings and grease was substituted for the oil as a lubricant, which proved quite satisfactory. However, the vibration which results from too much play in the bearings of the roller when operating at high speeds made it desirable to increase the life of these bearings as much as possible, so that, later, roller bearings with grease lubrication were installed with excellent results. As yet, these have not been in operation a sufficient length of time to indicate definitely how long they may be expected to last, but it would appear that the bearing will last much longer than the roller and that the attention required for the adjustment and lubrication of the bearing or the roller will be negligible.

On account of a decision of the mining company to divert to the Washoe smelter, at Anaconda, the shipment of approximately 3000 tons of ore per day that had previously been sent to the smelter at Great Falls, which will increase the ore traffic over the Butte, Anaconda & Pacific approximately 25 per cent, an extra motor-generator set, a duplicate of the original sets, has been installed in the Anaconda substation as a spare set, and four additional electric locomotive units were ordered and will be delivered within the next three months. These units will be duplicates of the original ones except that they are to be arranged for operating with an extra tractor truck attached when desired. This tractor truck will be a duplicate of the standard truck used under the regular units, with two standard motors mounted upon it with the necessary arrangements for coupling, both mechanically and electrically, so that the standard unit and the tractor truck may be operated as a single unit. The motors of the tractor truck are connected with those on the standard unit in such a manner as to place all six motors in series on the series points of the controller, and with a series-multiple connection with three motors in each series, on the multiple position of the controller. This arrangement will make the tractive effort of the new unit 50 per cent greater

than that of a standard unit for the same input, with a reduction in the free running speed of about 33⅓ per cent.

This arrangement was made advisable because of the increase in the weight of the trains taken up Smelter Hill, amounting to approximately 56 per cent. A single unit when used in the "spotting" service is taxed close to the slipping point of its wheels when accelerating these heavier trains on the 0.5 per cent grades under ordinary conditions of weather, and has to be handled very carefully with the continuous use of sand when the condition of the rails is unfavorable. Connecting the additional motors in series will also result in considerable power economy, since with a single unit the controller is seldom off the series resistance points, on account of the heavy trains handled and the short movements required.

Small change in the personnel of the maintenance or operating departments of the railway has been made on account of the electrification, nor has there been any reduction in salaries or wages. An extra man with electrical experience was placed in the shops to supervise the electrical repairs to the locomotives and three linemen were retained for the maintenance of the trolley system.

The three steam switching locomotives used for concentrating the ore at and distributing supplies from Butte Hill yards are continued in this work for reasons heretofore stated. Another steam locomotive is used on the Georgetown branch and a fifth one operates at intervals over unelectrified tracks at the Anaconda end. Approximately 20 per cent of the total locomotive-miles now being operated is by these five steam locomotives, the cost of which, as shown in Table VI, is upwards of 40 per cent of the total cost of all locomotive performance.

The electrification of the remaining tracks on Butte Hill has been recommended and no doubt will be commenced at an early date. Table VI referred to was made up from the regular monthly locomotive performance sheets of the railway company, from which the principal saving resulting from the electrification may be noted. The saving from the partial substitution of electric power for coal is the chief item, being at the rate of $150,727.04 per year, which is remarkable when it is considered that more than 39 per cent of the total combined costs for fuel and power for the period considered was for coal and charged against electrical operation. In this instance the saving on this item alone would undoubtedly justify the

TABLE V.

DELAYS TO TRAFFIC COMPARING THE MONTH OF JUNE 1913 STEAM OPERATION WITH JUNE 1914 ELECTRICAL OPERATION.

	Passenger Service.						Freight Service.								
June	No. of Trains	Delay for Meeting Points	Delay for Power	Delay Acct engine Failures	Lost Running Time	Total Delays	No. of Train	Terminal Delays and Switching	Delay for Power	Delay for Meeting Points	Delay due to derail-ments and break-in twos	Delay Account Eng. Failures	Delay Water and Coal	Total Delays	Grand Total Delays
		Hr. Min.	Hr. Min.	Hr. Min.	Hr. Min.	Hr. Min.		Hr. Min.	Hr. Min.	Hr. Min.	Hr. Min.	Hr. Min.	Hr. Min.	Hr. Min.	Hr. Min.
1st, 1913	14	43			18	1 : 1	14	12 : 15		4 : 55	30			17 : 40	18 : 41
1914	8						12	10 : 5		1 : 20	30			11 : 55	11 : 55
2nd 1913	8	42			2	44	8	12 : 5		2 :			35	14 : 40	15 : 24
1914	8	5	17			22	12	11 : 10	3 : 20	30				15	15 : 22
3rd 1913	8	15		14	5	34	12	9 : 30		4 : 30			10	14 : 10	14 : 44
1914	8						12	10 : 30		45		30		11 : 45	11 : 45
4th, 1913	8	10				10	12	11 : 28		3 : 50			19	15 : 37	15 : 47
1914	8	5				5	10	11 : 00		10		45		11 : 55	12 : 00
5th, 1913	8	17			5	22	12	14 : 00		4 : 45			40	19 : 25	19 : 47
1914	8	40				40	10	11 : 35		35				12 : 10	12 : 50
6th, 1913	8	1 : 10			3	1 : 13	14	13 : 25		3 : 10	1 : 05	24	40	18 : 44	19 : 57
1914	8						8	7 : 37		10				7 : 47	7 : 47
7th, 1913	12	07			51	58		11 : 20		6 : 30			40	18 : 30	19 : 28
1914	10	05			05	10	10	7 : 00		20		55		8 : 15	8 : 25
8th, 1913	13	36			37	1 : 13	13	12 : 38		5 : 20			40	18 : 38	19 : 51
1914							12	10 : 45		45	30			12 : 00	12 : 00
9th, 1913	8	24			8	32	12	12 : 15		2 : 05		1 : 15	10	15 : 45	16 : 17
1914	24	45		15	11	1 : 11	8	10 : 20		30	10			10 : 50	12 : 01
10th, 1913	8	22				22	12	10 : 20		3 : 30			11	14 : 40	[illegible]
1914	8						10	11 : 55		30	1 : 15			13 : [illegible]	[illegible]

12th, 1913	12	36				10	1 : 00	10	11 : 00		9 : 55		1 : 55	14	12 : 55	1 : 00
1914	23					9	09	4	3 : 35						3 : 35	3 : 44
14th, 1913	8							12	12 : 40		2 : 48			35	16 : 03	16 : 03
1914	10							8	7 : 40		10				7 : 50	7 : 50
15th, 1913	14	37				4	41	13	10 : 57		3 : 20	40	50	04	15 : 51	16 : 32
1914	8							8	6 : 55						6 : 55	6 : 55
16th, 1913	8	08				11	19	12	11 : 35		2 : 29	1 : 00		10	15 : 23	15 : 42
1914	8							8	7 : 50		10				8 : 00	8 : 00
17th, 1913	8	1 : 40					1 : 40	12	12 : 51		4 : 10	2 : 30		04	19 : 35	21 : 15
1914	8	17					17	10	9 : 50		10	20			10 : 20	10 : 37
18th, 1913	8	37					37	12	17 : 00		1 : 50			19	19 : 09	19 : 46
1914	8							8	7 : 55						7 : 55	7 : 55
19th, 1913	8	10					10	10	8 : 35		1 : 15			04	9 : 54	10 : 04
1914	8	15					15	10	10 : 05						10 : 05	10 : 20
20th, 1913	8	38					38	12	10 : 25		2 : 40			05	13 : 10	13 : 48
1914	10	30					30	10	10 : 30		30	45			11 : 45	12 : 15
21st, 1913	8	05					05	12	12 : 00		2 : 30				14 : 30	14 : 35
1914	10	22					22	8	7 : 45		25				8 : 10	8 : 32
22nd 1913	12	17				5	22	13	13 : 00		3 : 35			05	16 : 40	17 : 03
1914	8							10	10 : 40		15 : 00				10 : 55	10 : 55
23rd, 1913	8	05				13	18	12	10 : 25		4 : 00	40	1 : 41	35	16 : 51	17 : 09
1914	8							8	8 : 25		20 : 00				8 : 45	8 : 48
24th, 1913	8	40				16	56	12	11 : 18		2 : 00	2 : 00		35	15 : 53	16 : 49
1914	8	10	10				20	10	9 : 08		10				9 : 18	9 : 38
25th, 1913	8	1 : 00				02	1 : 02	12	12 : 35		4 : 20		42	14	17 : 51	18 : 33
1914	8	05					05	10	6 : 50		22	25			7 : 37	7 : 42
26th, 1913	8	1 : 06			30	03	1 : 39	12	13 : 25		5 : 05			14	18 : 44	20 : 23
1914	8	05					05	10	12 : 22		1 : 00				13 : 22	13 : 27
27th, 1913	8	23				11	34	12	12 : 21		3 : 15			14	15 : 50	16 : 24
1914	8				09		09	8	10 : 00		10				10 : 10	10 : 19
28th, 1913	8	48				07	55	10	12 : 35		4 : 20	40	1 : 00	10	18 : 45	19 : 40
1914	10	15					15	8	7 : 20						7 : 20	7 : 35
29th, 1913	10	35					35	13	13 : 00		2 : 05	15	20	15	15 : 55	16 : 30
1914	8							10	6 : 29		1 : 15				7 : 54	7 : 54
30th, 1913	8	27					27	12	11 : 50		1 : 40		15	20	14 : 15	14 : 40
1914	8	07					07	8	8 : 14			20			10 : 15	10 : [illegible]
Total 1913	279	13 : 09			45	1 : 13	11 : 49	297	299 : 58		[illegible]					

EXPENDITURES IN DETAIL AND PERFORMANCE OF LOCOMOTIVES—COMPARING SIX MONTHS STEAM

Month	Locomotive Miles					Maintenance of Equipment		
	Freight	Passenger	Switching	Non-Revenue and Special	TOTAL	Repairs.	Depreciation	Supervision
December, 1912, steam	23647	7031	27307	2152	60137	$ 9216.24	$ 1381.68	$ 587.7[illegible]
January, 1913, steam	26018	6956	28601	4228	65803	8391.12	1340.23	477.9[illegible]
February, 1913 steam	23514	6608	25041	4700	59863	9689.59	1340.23	512.77
March, 1913, steam	24948	7224	28136	6207	66515	8418.93	1340.23	559.8[illegible]
April, 1913, steam	23649	6832	21747	7802	60030	8884.76	1340.23	616.8[illegible]
May, 1913, steam	27167	7834	22667	10365	68033	6562.33	1340.23	393.0[illegible]
TOTAL 6 MONTHS STEAM	148943	42485	153499	35454	380381	$51,162.97	$ 8082.83	$3148.1[illegible]
Cost per locomotive mile cents—						13.45	2.12	0.8[illegible]
Cost per ton mile—cents						0.0644	0.0102	0.00[illegible]
December 1913, steam	3000	56	9683	6946	19685	$ 5567.97	$ 769.61	$ 431.4[illegible]
electric	35482	7280	16146	352	59260	1459.63		226.7[illegible]
Total	38482	7336	25829	7298	78945	$ 7027.60	$ 769.61	$ 658.1[illegible]
January. 1914 steam	3161		9242	2449	14852	$ 3577.93	$ 591.96	$ 271.2[illegible]
electric	36689	7264	15580	333	59866	1659.65		175.1[illegible]
Total	39850	7264	24822	2782	74718	$ 5237.58	$ 591.96	$ 446.4[illegible]
February, 1914 steam	3152		9068	1576	13796	$ 1638.43	$ 591.96	$ 185.1[illegible]
electric	33384	6608	15985	327	56304	2798.81	338.45	242.0[illegible]
Total	36536	6608	25053	1903	70100	$ 4437.24	$ 930.41	$ 427.1[illegible]
March, 1914 steam	3012		8584	2151	13747	$ 2035.95	$ 591.96	$ 170.6[illegible]
electric	34664	7336	14279	363	56642	3064.40	2711.13	222.8[illegible]
Total	37676	7336	22863	2514	70389	$ 5100.35	$ 3303.09	$ 393.6[illegible]
April, 1914, steam	2415	348	8001	2175	12939	$ 1461.39	$ 591.96	$ 178.1[illegible]
electric	34098	7024	12883	768	54773	3076.05	2711.13	314.5[illegible]
Total	36513	7372	20884	2943	67712	$ 4537.09	$ 3303.09	$ 492.7[illegible]
May, 1914 steam	1569	16	8485	920	10990	$ 1017.37	$ 591.96	$ 135.6[illegible]
electric	36087	7658	13931	107	57783	3763.93	2711.13	262.5[illegible]
Total	37656	7674	22416	1027	68773	4781.30	$3303.09	$ 398.2[illegible]
TOTAL 6 MONTHS—								
STEAM	16309	420	53063	16217	86009	$15299.04	$ 3729.41	$1372.4[illegible]
ELECTRIC	210404	43170	88804	2250	344628	$15822.47	8471.84	1443.8[illegible]
TOTAL	226713	43590	141867	18467	430637	$31121.51	$12201.25	$2816.2[illegible]
Costs per locomotive mile, steam—cents—						1778	4.34	1.5[illegible]
Cost per locomotive mile, electric—centre—						4.59	2.46	0.4[illegible]
Average costs per locomotive mile, combined steam and electric—cents						7.23	2.83	0.6[illegible]
Average costs per ton mile, combined steam and electric—cents						0.0360	0.0141	0.003[illegible]
Decrease shown in favor of electrical operations	77770*	1105*	11632	16987	50256*	$20041.46	$ 4118.42*	$ 331.8[illegible]
Savings resulting per year on the above basis—decreased operating expenses						$40082.92	$ 8236.84*	$ 663.7[illegible]
Percentage of saving account of electrical operation decreased operating expenses						39 17	50.95*	10.5[illegible]

*Increase.

1,

1 To May, 1913, Inclusive With Six Months Electrical Operation—Dec. 1913, to May, 1914, Inclusive.

	Transportation Expenses									
of Engines.	Eng'h'se Expenses	Fuel and Power	Water	Lubrication	Other Supplies	Total	Grand Total	Tons Coal	Kw-Hr.	Ton Miles
18.11	$ 2533.91	$26259.02	$342.51	$ 683.21	$ 482.88	$ 38917.64	$ 50103.35	6149		13,182,40
9.10	2814.96	29085.78	353.15	761.38	499.84	42608.21	52817.24	6938		13,167,78
9.06	2530.88	26150.98	436.89	864.73	595.36	39207.90	50750.49	6241		12,014,15
8.47	2637.11	26893.72	543.34	851.20	466.73	40060.57	50379.70	6431		13,406,29
7.15	2184.17	23690.52	395.55	790.95	426.20	35624.54	46466.39	5610		13,371,72
6.70	2252.87	25537.85	405.39	924.25	440.75	38647.81	46943.45	6022	39,748	14,316,51
0.59	$14953.90	$157617.87	$2476.83	$4875.72	$2911.76	$235066.67	$297460.62	37400	39,748	79,458,86
8.73	3.93	41.43	0.65	1.28	0.77	61.79	78.19	10.17 locomotive miles per to		
.0667	0.0188	0 1984	0.0031	0.0061	0.0037	0.2958	0.3743	2125 ton miles per ton of co		
2.80	$ 780.46	$ 7529.39	$ 188.95	$ 263.70	$ 255.30	$ 11840.60	$ 18609.59	1770		
8.25	1116.73	8605.81		182.73	215.63	14283.15	15969.51		1,558,800	
9.05	$ 1896.19	$ 16135.20	$ 188.95	$ 446.43	$ 470.93	$ 24123.75	$ 34579.10	1770	1,558,800	14,024,00
4.70	$ 674.83	$ 6436.32	$ 96.00	$ 221.14	$ 189.24	$ 9822.23	$ 14263.39	1415		
0.35	859.76	8952.53		184.33	194.51	14231.48	16066.31		1,670,248	
5.05	$ 1534.59	$ 15388.85	$ 96.00	$ 405.47	$ 383.75	$ 24053.71	$ 30329.70	1415	1,670,248	15,210,01
1.55	$ 479.88	$ 5960.36	$130.41	$ 196.98	$ 122.69	$ 9031.87	$ 11447.39	1394		
0.65	926.75	8210.53		166.40	135.88	13300.21	16579.48		1,487,200	
2.20	$ 1406.63	$ 14170.89	$130.41	$ 363.38	$ 258.57	$ 22232.08	$ 28026.87	1394	1,487,200	13,715,90
4.15	$ 369.39	$ 5571.85	$ 77.40	$ 205.48	$ 156.62	$ 8414.89	$ 11213.61	1276		
2.50	1177.76	8149.25		176.46	203.19	13460.16	19458.51		1,476,100	
6.65	$ 1547.15	$ 13721.10	$ 77.40	$ 381.94	$ 359.81	$ 21875.05	$ 30672.12	1276	1,476,100	14,274,06
5.72	$ 458.48	$ 2828.32	$ 89.65	$ 198.61	$ 138.05	$ 5688.83	$ 7920.36	608		
6.42	1183.45	7918.48		246.87	221.80	11056.02	19157.74		1,434,300	
1.14	1641.93	$10746.80	$ 89.65	$ 445.48	$ 359.85	$ 11744.85	$ 27078.10	608	1,434,300	14,721,48
0.10	$ 424.90	$ 4162.17	$ 14.44	$ 149.14	$ 209.38	$ 6656.13	$ 8401.13	1898		
4.75	867.80	7929.34		279.32	233.89	12845.10	19582.69		1,436,270	
0.85	$ 1292.70	$12091.51	$ 14.44	428.46	443.27	$ 19501.23	$ 27983.82	1898	1,436,270	14,482,43
3.02	$ 3187.94	$32488.41	$596.85	$1235.05	$1071.28	$ 51454.55	$ 71855.47	8361		
7.92	6131.25	49765.94		1236.11	1204.90	81076.12	106814.24		9,062,918	
3.94	$ 9319.19	$82254.35	$596.85	$2471.16	$2276.18	$132530.67	$178669.71	8361	9,062,918	86,427,92
4.97	3.71	37.78	0.69	1.44	1.24	59.83	83.55	10.29 Loco. miles per ton of c		
6.60	1.78	14.44	0.00	0.36	0.35	23.53	31.00	26.30 kw. hrs. per locomotive mile		
6.27	2.16	19.10	0.14	0.57	0.53	30.77	41.48			
.0412	0.0108	0.0952	0.0007	0.0028	0.0026	0.1633	0.2067			
7.65	$ 5634.71	$75363.52	$1879.98	$2404.56	$ 635.58	$102536.00	$118790.91	29039	9,023,170*	6,969,06
5.30	$11269.42	$150727.04	$3759.96	$4809.12	$1271.16	$205072.00	$237581.82			
1.81	37.68	47.81	75.90	49.31	21.83	43.62	39.93			

[coz]

Operating Expenses—Comparison of Six Months Steam Operation—Dec. 1912 To

		December	January	February	
Maintenance of way and structure,	1913	$11233.82	$13252.96	$10885.20	$
	1914	14377.32	10107.61	9607.83	
	Decrease	$ 3143.50*	$ 3145.35	$ 1277.37	$
Maintenance of equipment,	1913	$21824.74	$24012.20	$26219.97	$
	1914	23765.83	18472.16	17281.41	
	Decrease	$ 1941.09*	$ 5540.04	$ 8938.56	$
Traffic expenses,	1913	$ 760.84	$ 877.49	$ 640.02	$
	1914	703.55	613.98	548.86	
	Decrease	$ 57.29	$ 263.51	$ 91.16	$
Transportation expenses	1913	$56171.03	$63864.94	$57377.42	$
	1914	47772.32	44243.99	41529.43	
	Decrease	$ 8398.71	$19620.95	$15847.99	$
General expenses	1913	$ 3218.70	$ 2462.68	$ 2621.97	$
	1914	2963.73	3185.52	4948.42	
	Decrease	$ 254.97	$ 722.84*	$ 2326.45*	$
Total Operating Expenses	1913	$93209.13	$104470.27	$97744.58	$
	1914	89582.75	76623.26	73915.95	
	Decrease	$ 3626.38	$ 27847.01	$23828.63	$
Net operating revenue	1913	$18075.01	$ 4518.47	$ 7121.88	$
	1914	43271.31	54232.62	48926.12	
	Increase	$25196.30	$ 49714.15	$41804.24	$
Taxes	1913	$ 2638.58	$ 2000.00	$ 2000.00	$
	1914	3205.50	2500.00	2500.00	
	Increase	$ 566.92	$ 500.00	$ 500.00	$
Operating income	1913	$15436.43	$ 2518.47	$ 5121.88	$
	1914	40065.81	51732.62	46426.12	
	Increase	$24629.38	$ 49214.15	$41304.24	$

† Increase
* Decrease

...ES WITH SIX MONTHS ELECTRICAL OPERATION—DEC. 1913 TO MAY, 1914.

...ril	May	Total 6-months.	Average for 6-months period.		
			1913	1912	1911
22.78 56.17	$10579.15 17749.74	$63316.64 75857.03	$66945.57	$81284.00	$62028.28
13.39*	$ 7170.59*	$12540.39*			
20.93 31.79	$19042.16 24559.16	$133475.43 133952.88	$132596.39	$109495.65	$103796.27
71.66*	$ 5517.00*	$ 477.45*			
1.27 3.37	$ 661.06 585.71	$ 4164.53 3804.22	$ 4224.42	$ 4371.95	$ 3727.60
19.00*	$ 75.35	$ 560.31			
2.39 6.18	$50912.60 37925.38	$333516.33 250527.46	$315555.24	$259948.95	$241571.49
6.11	$12987.22	$ 82088.87			
4.69 .18	$ 2727.64 4132.90	$ 17062.31 25107.60	$ 18265.85	$ 17646.52	$ 13874.55
1.49*	$ 1405.26*	$ 8045.29*			
.96 .59	$83922.61 84952.59	$551535.24 489049.19	$537587.41	$472747.07	$424998.19
.47	$ 1030.28*	$ 62486.05			
.34 .18	$41280.07 39606.23	$121578.28 265553.68	$127882.70	$103692.27	$111106.97
1.94	$ 1673.84†	$144075.40			
.00 .00	$ 2000.00 2500.00	$ 12638.58 15705.50	$ 12319.29	$ 12881.99	$ 12306.88
.00	$ 500.00	$ 3066.92			
.34 .18	39280.07 37106.23	$108939.70 249948.18	$115563.42	$ 90810.28	$ 98210.09
.84	$ 2173.84†	$141008.48			

[cox]

expenditure covering the entire cost of electrification. It is to be noted that with a single exception, that for depreciation of equipment, every item of expenditure in the locomotive performance sheet shows a substantial percentage of decrease in favor of electrical operation.

It is the practise of the railway company to adjust depreciation charges on all locomotives at the beginning of each half year. The amount to be charged to the depreciation of a new locomotive for the first half year it is in service is determined by taking a fixed percentage of its cost to the company, one-sixth of this amount being charged against the locomotive each month for the half year, at the end of which the amount of the depreciation for the period is deducted from the original cost of the locomotive to give a new value, of which the original fixed rate of percentage is taken in determining the amount of the depreciation for the following half year, and so on.

The Interstate Commerce Commission ruling does not permit a depreciation charge until the locomotive actually becomes the property of the railway company and as the electric locomotives were not formally taken over by the company until March, 1914, the proper monthly charge begins only with that month in the regular monthly performance sheet from which Table VI was compiled. In fairness to the performance sheet, only the proper monthly depreciation charges were made, but as some of the locomotives had been in service eight months before these charges began, an adjustment was necessary to make a proper distribution of the back depreciation, so that while Table VI shows only the proper monthly charge for the six months compared, amounting to $8,471.84, in Table VII under "maintenance of equipment" the total back charges were included, amounting to $20,047.48. It is evident that the depreciation reckoned on this basis for the first months of service would be comparatively high.

The total saving from locomotive performance alone as indicated by Table VI is at the rate of $237,581.82 per year, to which should be added the credit of handling an increase of traffic at the rate of 13,938,136 ton-miles per year or 8.77 per cent more than was handled by the steam locomotives during the period compared. To this saving from locomotive performance should be added the saving from trainmen's wages, which is at the rate of $31,146.30 per year, or a decrease of approximately 21 per cent, due largely to the elimination of

overtime (Tables I and II), making the total saving from these two items $268,728.12 per year. From this should be deducted $10,839.12 for maintenance of the distribution system, leaving $257,889 as the net operating saving per year due to electrical operation.

The roadmaster states that it is quite evident that the electric locomotives are much easier on the track at curves but that there is no noticeable difference on tangent track, and that while sufficient time has not yet elapsed to form definite conclusions, present indications lead him to expect that any difference relative to his work will be favorable to the electric locomotives.

Arranging the items of expense appearing in Table VI in the order of usual appearance in the summary of a standard locomotive performance sheet, and placing them on a yearly basis, results as follows:

Item of Operating Expenses	Steam 1913	Electric 1914	Decrease 1914	Per cent decrease
Fuel and power	$315,235.74	164,508.70	150,727.04	47.81
Repairs	124,787.90	92,278.08	32,509.82	26.05
Enginemen's wages	104,461.18	71,125.88	33,335.30	31.81
Enginehouse exp.	29,907.80	18,638.38	11,269.42	37.68
Water	4,953.66	1,193.70	3,759.96	75.90
Lubricants	9,751.44	4,942.32	4,809.12	49.30
Other supplies	5,823.52	4,552.36	1,271.16	21.83
TOTAL LOCOMOTIVE PERFORMANCE	$594,921.24	$357,339.42	237,581.82	39.93
Trainmen's wages	147,632.30	116,486.00	31,146.30	21.10
GRAND TOTAL	742,553.54	473,825.42	268,728.12	36.19
Ton-miles hauled	158,917,720	172,855,856	13,938,136*	8.77*

*Increase

The total cost of the electrification, including a change of signal system on Smelter Hill, the extra motor-generator set recently installed at Anaconda, interest during construction and all incidentals due in any way to the electrification, was in round numbers $1,201,000. This does not include the step-down transformers, which are the property of the power company, but on the other hand no deduction has been made for the salvage due to the elimination of 20 steam locomotives.

If a correction be made for the item of depreciation in Table VI, charging the regular monthly amount of $2711.13 begun in March for each of the six months, making the total of this item

for the period $16,266.78 instead of $8,471.84 as it stands on the performance sheets, the total saving per year from locomotive performance would be reduced to $221,991.94, making the total net saving $242,299.12, which is equivalent to 20.02 per cent on the entire cost of the electrification, to say nothing of the increased capacity of the lines, the improvement in the service and more regular working hours for the crews, as is indicated in Table V, comparing the delays to traffic, and Tables I and II, showing the decrease in overtime.

From Table VII it will be seen that if taken on the basis of the increase shown in net operating revenue, or operating income, this percentage is slightly greater, the rate of increase per year for these items being $288,150.80 and $282,016.96, respectively.

The estimate on which the decision to proceed with the electrification of the road was made, placed the annual net saving expected at 17.5 per cent of the cost, so that the results financially have been quite as satisfactory as the general performance of the equipment.

DISCUSSION ON "ELECTRIFICATION OF THE BUTTE, ANACONDA AND PACIFIC RAILWAY" (COX), SPOKANE, WASH., SEPTEMBER 10, 1914.

Paul Lebenbaum: This paper looms up as an oasis of facts in a desert of glittering generalities, and records a distinct step forward and upward in heavy railway electrification. It is unique in that it sets forth, not only facts, but actual figures on operating results, for a road that made the change from steam to electricity solely in order to obtain increased capacity and greater economy in operation. Most, if not all, of the heavy electrification has been done for the purpose of overcoming an operating condition for which steam was unsuited, such as the New York terminal electrifications, the work of the Great Northern at the Cascade Tunnel, etc. It must therefore be peculiarly gratifying to the management and its engineers that the economies resulting from the change were so quickly and positively established.

It would, no doubt, take some time to properly correlate and digest the many figures that Mr. Cox has presented; what little I have to contribute to the discussion will therefore be in the nature of a comparison with some of the results obtained on the Portland, Eugene & Eastern Railway, operating at 1500 volts over some 105 miles of single-track road, exclusive of sidings. All passenger movements are electric, freight being still handled by steam, the speeds in passenger service exceeding 50 miles per hour.

It appears that 90 per cent of the B. A. & P. train mileage is made in freight service at the comparatively low speed of 16 to 17 miles per hour, while all of our passenger service is at much higher speeds. Both roads use the US-122-E. type of pantograph, having a five-inch diameter roller, as a current collector, the B. A. & P.'s problem being to pick up large currents at low speeds and the P. E. & E.'s smaller currents at high speeds.

We make approximately 45,000 train miles, or 120,000 motor car miles, per month. Each motor car uses its pantograph, there being no power bus on our equipments. I was therefore interested in Mr. Cox's statement as to the average life of collectors being 10,000 to 12,000 miles. We have also found it necessary to equip our collectors with a roller type of bearing, discarding the graphite bushings originally furnished. Since that time we have made well over 20,000 miles each on enough collectors to convince us that 50,000 miles should be the average collector life under our conditions, where each motor car takes from 100 to 150 amperes. It no doubt is reasonable to assume that the smaller mileage made by the B. A. & P. rollers is in part due to the heavier currents they must collect; although the lower speeds made by 90 per cent of their rollers should, to my mind, somewhat offset this latter condition.

The whole subject of current collection, in small or large quantities at high or low speeds respectively, presents a very

interesting problem, the solution for which, at least in this country, is yet to be found.

I noted that equipment trouble on the 2400-volt locomotives was negligible. We have also had practical freedom from serious troubles; in one or two instances arcs from the circuit breakers have jumped to ground, due entirely to the method of venting the gases engendered by the breaking of the current. I ask Mr. Cox whether the B. A. & P. has had any similar experiences in the breaking of high-voltage arcs.

C. P. Kahler: I note that a comparison has been made between the electric and steam operation costs of the Butte, Anaconda & Pacific Railroad, and that a 20 per cent earning on the investment for electrification is shown, based on the first six months' records of the operating expenses. I would hardly think that a comparison based on six months' records would give a correct idea of the relative costs of electric and steam operation of this railroad. For instance, take the item of locomotive repair costs, which are usually divided into two parts, light running repairs and shop or heavy repairs. Six months' service with electric locomotives would give very little, if anything, on the shop or heavy locomotive repairs, and consequently I would judge that the electric locomotive repair expense for the first six months would necessarily be considerably less than will be the case after the locomotives have been in operation several years and sent through the shops once or twice. I have noticed that the repair costs of steam locomotives usually start out at a very low figure per locomotive-mile, and gradually increase, as the locomotive gets older, until the cost per locomotive-mile will quite often reach several times the cost when the locomotive first began operating. Consequently I would hardly think it proper or fair to the steam locomotive operation to compare the first six months' expenses of the new electric locomotive operation against the cost of maintaining a few old steam locomotives.

The steam locomotives used in operating the Butte, Anaconda & Pacific were not very large when compared with the size of the steam locomotives used on many other railroads, and it would be interesting to know what saving would have been made by replacing the old steam locomotives of the B. A. & P. with new and larger steam locomotives, and also what would be the saving by electric operation as compared with steam operation, using large steam locomotives.

For some time past I have been of the opinion that the greatest saving which would result from electric operation of steam railroads would be from the reduction in the steam train service, and the data given in Mr. Cox's paper tend to confirm this opinion, for by electric operation three crews are now hauling the same tonnage as four crews did with steam locomotives, a reduction of about 25 per cent in the train service. As the train crew expense on most roads is usually somewhat near

20 per cent of the total operating cost of the railroad, a reduction of 25 per cent in this expense by electric operation would mean that the total expense of steam operation would be reduced about 5 per cent on account of the reduction in train service alone. Additional saving would, of course, be made on account of the lower cost of locomotive repairs, less engine house expense, and other detailed costs which would result by electric operation.

I note that electric locomotives with four axles, having a combined weight of 80 tons, are used on the B. A. & P. R. R., and that two of these four-axle units are rated as one locomotive of 160 tons. I judge that units of this weight were selected in order to allow one pantograph per unit for collecting current. However, it would appear to me better, in determining the weight of an electric locomotive, to work from the other end. In other words, to determine the maximum weight which your track would support, and make the axle loads of the electric locomotive correspond to this. For instance, the Union Pacific system allows a maximum weight on locomotive drivers of 55,000 pounds, which would make a four-unit locomotive, similar to the B. A. & P. electric locomotives, weigh 110 tons on the drivers, a fairly large size locomotive. The Pennsylvania, I believe, allows as high as 65,000 pounds on each driver, which would make the total weight of a four-driving-axle locomotive equal to 130 tons on the drivers. This would be nearer my idea of a locomotive which would be best fitted for the freight service. This would also make the use of the tractor auxilary referred to, unnecessary.

In conclusion, I would say that while I do not consider the results as absolutely conclusive, the paper is very valuable in that it bears out many claims made as to the advantages and lower economy which would result from electrically operating steam railroads. Further, the fact that the B. A. & P. R. R. is simply a short line would not be an especially favorable condition for expenditures in electric traction work, and the favorable showing which is evidenced by the data given in Mr. Cox's paper would probably be very much better if applied to an engine district of about 150 miles in length, and under such conditions I believe that the earnings which would be made on the investment for electrification work would in many cases exceed the 20 per cent which Mr. Cox claims as the earnings on the investment from the electric traction work of the Butte, Anaconda & Pacific Railroad.

J. C. Ralston: The author designates the engineman, the man who drives the locomotive, as a locomotive engineer, and again he speaks of him specifically as an engineer, I think. Now, 90 per cent of engineers are responsible for an incorrect use of that word. I feel this: that if the four premier engineering societies, namely, the electrical, civil, mechanical, and mining, would all take up this question and use the proper word,

we would not be confused as we are by reading in the papers of the hoisting engineers' society and the various societies in domestic lines. I hope that the engineers themselves will follow the correct terminology and then the public will later follow our lead.

A. A. Miller: I ask Mr. Cox to give us a little more description of those tractors; do they have cabs?

W. K. Stacy: I wish to inquire regarding the life of the trolley wire when using the roller collector. I have had experience with the sliding collector and under certain conditions the wear on the trolley wire was excessive. This was particularly apparent with rigid hangers at the ends of line circuit breakers. What style of trolley wire suspension is used on the B., A. & P?

Paul Lebenbaum: After the line had been in operation for about five months, the trolley wire was carefully calipered to determine whether there had been any wear, especially at what might be called hard spots in the line. No measurement taken showed a variation from the true diameter of the wire greater than the 2 per cent variation allowed the manufacturer under our specifications.

J. B. Cox: Referring to the remarks relative to the steel rollers used for the collection of current on the pantographs, these collect 600 amperes at from 16 to 20 mi. per hr. quite satisfactorily. It would be rather difficult to compare the life of the rollers used on the Butte, Anaconda & Pacific locomotives with similar rollers on ordinary interurban cars where they are required to collect a much smaller current and at somewhat higher speeds. The heavier currents required in the operation of the locomotives would undoubtedly account for the much shorter life in this case. The 10,000 to 12,000 miles being obtained from the rollers on the locomotives is equally as great as was expected of them when it was decided to install this type of collector.

As compared with the slider type of collector, the roller is considerably heavier and somewhat more complicated, but on account of its longer life and less wear on the trolley wire in the heavier class of service it has been considered more desirable for the collection of heavy currents. It is generally admitted that the slider is more simple and if it can be perfected so as to collect an equal amount of current with even half the life in mileage obtained from the roller and with equal wear on the trolley it will usually be preferable and would no doubt prove more economical both as regards first cost and maintenance. Considerable progress is being made in the development of a sliding pantograph in the above respects and I am of the opinion that their use will become more general. I have recently seen up to 3000 amperes collected without sparking by a single pantograph with a double sliding collector. This was on the occasion of test running, which gave most promising indications

of practical success, but actual service under general operating conditions will be necessary to perfect these sliders in every detail. Personally, I have no doubt but that either type of collector can be made to operate quite successfully under almost any practical conditions.

As to the number of linemen employed in the maintenance of the distributing system, I have given the exact number regularly retained on the pay rolls of the company. The amount stated as being the cost of maintenance of the distributing system was based on the rate of the monthly charges for the six months for which the operating costs are given and cover all items chargeable to this account, which are principally for material, labor and work-train service. These costs are at the rate of approximately $125.00 per mile per year and are about what is expected to be the average cost for at least the normal life of the wooden poles, which is expected to average in this locality from twelve to fifteen years.

In reference to the wear on the trolley wire, this is so small to date that any statement as to actual measurements would be of small value, since the allowable variation in the diameter of the new wire might easily make such figures misleading unless careful measurements had been made and recorded before the electrical service was started. This wear will usually be noticeable first at hard spots in the line where there are pull-offs or rigid hangers. The construction of this line was designed with a special view to flexibility, so as to facilitate the operation of the roller collector as well as to reduce the wear on the trolley, and undoubtedly it is the most flexible construction of the kind in this country at the present time.

Relative to the suggestion that the first six months of electrical operation is too short a time on which to base definite comparisons, I have not stated that such is to be done, but I have given actual figures from official records accompanied by an explanation of the principal conditions under which the results were obtained.

The last six months' full steam operation has been compared with the first six months' full electrical operation and it just so happens that the changing-over period lasted six months, making the comparison for the same months of consecutive years. The systems of accounts were kept identical so that results would be directly comparable; the same men have taken care of the maintenance and done the operating in each case and very much in the regular way, making only such changes as were naturally suggested from the use of the new motive power, and the entire change has been made so gradually that I doubt very much if there has heretofore been such favorable opportunity for obtaining operating costs where so direct a comparison between steam and electric locomotives could be made.

In the first place the conditions for segregating the costs have seldom been so favorable, and secondly, operating companies that would give out such full information have been exceptional.

Precisely the same conditions might not be met on another road, hence exactly similar results would not be expected. The extent of the usefulness of these figures in forecasting results of proposed electrifications depends upon our ability to properly adjust them to apply to any other particular case. It has been suggested that the cost of repairs to the electric locomotive for the period considered is less than it will be in the future and that for this reason the comparison of these items might not be representative, it being unfair to compare the cost of repairs of new electric locomotives with that of steam locomotives which have been in service a number of years. While this is not an unnatural inference, in practise I have not usually found it to be true and in this particular instance I feel confident that the cost of maintenance of the electric locomotives given in Table VI, which includes the charge for depreciation, will be less in the future than it has averaged for the six months in question. The reasons on which this expectation is based are, first: that of the total cost per locomotive mile, amounting to 7.47 cents, 2.46 cents is for depreciation, leaving 5.01 cents as the cost per mile for actual repairs as the term is generally applied. This is fairly high under ordinary conditions but not unreasonably so here under the special circumstances, as it included the cost of considerable experimenting with pantograph rollers and minor improvements to the equipment in adapting them to the special conditions required by the service; so that on the whole about as much work has been done on the locomotives during these six months as will be averaged at any time in the future and the decrease in the rate of depreciation on the basis that it is being determined will more than take care of any probable increase in actual repairs.

Secondly, the old steam organization was retained as far as required for the maintenance of the electrical equipment. It would be unreasonable to expect that they will not improve in efficiency as they become more familiar with the new equipments, and the shop facilities will be gradually improved also, resulting in reducing the cost of repairs on the electric locomotives.

Taking all these circumstances, with which I am familiar, into consideration, I shall be very much disappointed if the cost of maintenance of the electric locomotives per mile operated does not show a gradual decrease during the next few years. I have had considerable experience in connection with the initial operation of electric locomotives and their maintenance during the first two or three years in service, and this experience has led me to the conclusion that the cost of maintenance of an entirely new type of equipment in the hands of an old steam organization will usually be equally as high the first year as the average cost for a number of years after. This is particularly the case where dual equipment is operated and where the costs of minor developments and adaptations are taken care of and charged to the maintenance department. When utiliz-

ing the old organization under such conditions, it is a mistake not to begin a regular system of general inspection and repairs at the very beginning so as to get the men as familar with the new apparatus as possible, so that when these repairs are actually necessary they will not only have a definite idea of the work ahead of them but will also be provided with the necessary tools so that they can do the work with the same efficiency as in the case of the steam locomotives. On the whole I have found it more easy to break in old steam organizations to operate and take care of electric locomotives than to adapt electrical men to the work who had not had previous steam railway experience.

It might be of interest to state here that at the end of a year's service a general shop inspection and overhaul of the electrical locomotive was begun with this object in view. The trucks were taken out from under the cab, the motors taken off, the armatures taken out and every thing gone over as thoroughly as possible, including the turning of tires and rebabbitting of armature bearings.

This was done corresponding to similar annual general overhaul of a steam locomotive. The electric locomotive was in the shop one week, whereas four weeks were required on an average for the steam locomotives for a similar overhaul, and the costs in each case were about proportional to the time the locomotives were in the shops; that is, the electric locomotive cost was about one-quarter that of its steam predecessor. The tires on the drivers of the electric locomotive will average somewhat more than double the mileage between turnings obtained from those under the steam locomotive.

The many sharp curves on the entire system result in rapid wear of the flanges.

While I have had little actual experience in connection with the maintenance of new steam locomotives, I have often had occasion to investigate the costs of repairs to steam locomotives. My impression is that on the first installation of a new type of steam locomotive on any road the adaptation and development charges during the first year are apt to make up for the smaller number of general repairs that are required during the first year, much the same as in the case of the electric locomotives. As an instance I will cite the case of a number of large Mallet engines, the cost of repairs for which was 20.46 cents per mile for the first six months, whereas the average cost during the first four years of their service was 23.34 cents. The cost for the second year was greatest while that for the third year was least. I do not believe this is exceptional. In the case of electric locomotives I have in mind a record in which the cost of repairs the first year was 6.7 cents per locomotive mile and for the fifth year 4.1 cent, the average for the five years being 4.85 cents; and another where the cost for the first six months was 5.45 cents per mile and the average cost

for the fourth year was 4.98 cents. Both these instances were steam road electrifications with new 600-volt equipment. As a matter of fact most of the records I have seen are of a similar nature, and it is these facts coupled with actual experience that are responsible for my opinion on the subject.

It would be only natural to expect that the cost of maintenance on steam locomotives, during the last six months they were expected to be used, before being replaced by electric locomotives, would be somewhat neglected, and hence the costs per locomotive mile would be less than the average. However, I investigated the records over a considerable period of steam operation and found no very great variation on account of this, but that the figures for the six months quoted were fairly representative.

In this connection it may be stated that the Butte, Anaconda & Pacific Railway has always kept its locomotives in an unusually good state of repair and that the prices paid for all classes of labor are perhaps higher than is paid anywhere else in this country. The fact that the cost of labor is high is not altogether favorable to the electrification, inasmuch as it greatly increased the first cost, but insofar as the operation of transportation and maintenance of locomotives is concerned, it is more favorable, since the number of employees is generally reduced to some extent and the overtime is apt to be considerably less.

Referring to the suggestion that the electric locomotive units should have been larger, this subject was very carefully considered before the design of the locomotive was begun and after an investigation of all the conditions and the general requirements of the work it was agreed that a unit approximating 80 tons on the drivers would give best general results and that no advantage offered by a heavier unit for any part of the service would offset the disadvantages of a mixed type of equipment. Electric units weighing 100 tons are quite common, and the three-phase electric units which have now been in operation on the Great Northern Railway for five years weigh 115 tons each, all of which is on four axles, so that ordinarily there should be no difficulty in providing as heavy a unit as conditions might require. In the case of a mountain division on a transcontinental line it is usually desirable to use as heavy units as the draft gear of the rolling stock will permit. In the case of the B., A. & P. Railway the conditions were not considered generally favorable for the use of larger units. Longer trains than could be handled by a double 80-ton unit locomotive would have required the lengthening of yards, sidings and passing tracks. Heavier units in this case would also have increased the peak loads on the substations and lowered the load factor. The draft gear on the ore cars and many other local conditions had to be considered in this connection, the general result of which led to the adoption of the present unit.

Referring to the burning out of contactors, due to dust or irregularity in following the proper sequence of operation, there have been no instances of serious trouble with contactors, from any causes, so far as I am aware. There have been instances of flashing over of insulators at the back of the contactors, which was thought to have been due to the accumulation of dust from the ore, which contains some copper. There is, naturally, a great deal of such dust, and the blowers located in the cabs of the locomotive cause more of it to be drawn over the apparatus than would be done otherwise. We had really expected much more trouble from this source than actually occurred. These arc-overs did not result in any serious damage. It was only on inspection that it was found the insulators had arced over, as apparently the arcing had occurred when the contactors were opening the circuit so that the current was shut off before the arc did any thing more than burn off the dust, after which there was no further bother.

In one or two instances where the main trolley contactors were involved, the main fuse was blown, but as far as I am aware no contactors have been damaged so as to cause any delay or to require immediate attention. In this particular control equipment the transition between series and parallel connections, where troubles from improper sequence of coming in and out of contactors are most likely to occur, the contactors involved in the transfer are operated by means of a cam which insures a proper and uniform sequence and no troubles whatever have been experienced from this source.

During the first ten months of operation no contact tips had been changed on any of the contactors nor had any repairs to same been necessary. On the whole the contactors on the locomotives show less signs of arcing or burning than on an ordinary 600-volt locomotive in a similar service.

The commutators of the main motors are in such splendid condition that during the visit of some German engineers to inspect the electrification about six months after the locomotives had been in operation, it was difficult to convince them that the commutators had not recently been turned.

Relative to the term "engineers" as used when referring to the drivers of the electric locomotives, it is in accord with steam road practise, as has been the intention all through. Steam operators will be equally interested with the electrical man in the results and the terms used and comparisons made throughout are meant to be equally clear to both.

Table VI is made up to conform to the usual steam railway locomotive performance sheets and practically the same form was retained for the electric locomotives in order that the comparisons relative to the performance of each might be as direct as possible.

The passenger locomotive miles and the passenger train miles on the Butte, Anaconda & Pacific Railway are the same, as only a single unit is used to haul the passenger trains.

Referring to Table VI, it will be seen that the electric locomotive miles made in passenger service for the six months considered were 43,170, which is approximately 12.5 per cent of the total miles operated by all electric locomotives for the period.

The tractor trucks which are to be supplied with the new locomotives on order for the spotting and switching service will be arranged for coupling onto a standard locomotive unit much as an extra motor car is added to a multiple unit train, except that the electrical connections between the unit and the truck will be such as to connect the motors mounted on the latter in series with those on the former, instead of in multiple as in the case of the extra car in a multiple unit train.

In other words, it will form a three-truck locomotive with six motors, arranged for all six to be operated in series on the usual series points of the controller and with a series-multiple connection consisting of two circuits of three motors each on the usual parallel points.

This plan was considered preferable to adopting a special three-truck locomotive since when the extra truck is detached the unit is interchangeable with all others, or any of the existing units can be arranged for operation with the extra truck by the provision for the necessary electrical connectors.

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APPLICATION OF ELECTRIC MOTORS TO GOLD DREDGES

BY GIRARD B. ROSENBLATT

ABSTRACT OF PAPER

Electric power has been applied almost universally to the operation of gold dredges of late, owing to its convenience and to the fact that hydroelectric power is available at very reasonable rates throughout the western states where gold dredging is carried on. There are a number of different motor applications on the elevator type of gold dredge, which is the type most generally used, and the author considers very fully the requirements of the various drives and the characteristics of the motors suited to the various operations of these dredges. Alternating-current motors are generally used for these purposes and the type of control, which is of special importance, is considered. The paper also gives some figures on the cost of operation of dredges of different capacities.

A GOLD dredge is a piece of machinery designed to dig gold-bearing gravel, sand, or clay, and to treat the material so dug in such a way as to recover the gold contents. It, accordingly, consists essentially of two parts; one the digging part and the other the gold-saving part.

From the point of view of the application of electric power the digging end is of particular interest as the mechanical requirements are severe and the speed control must be exceptionally good. The gold-saving end does not differ very materially as to motor applications from those of the usual metal mining mills, except possibly that the equipment is exposed to a little more abuse and that compact methods of drive are necessitated.

Electric power has been applied quite universally of late to the driving of gold dredges owing to its convenience and economy. Of the $88,400,000.00 worth of gold produced last year in the United States, nearly a fifth came from gold dredges, and in view of the fact that gold is being mined by means of dredges in practically all of the Western States, in most of which localities hydroelectric central station power is available, a few remarks regarding the essential characteristics of successful motor drive may be of interest.

In designing electrical apparatus and applying it to gold dredging, the electrical engineer is often too prone to approach the problem from the point of view that the dredge should be designed particularly to permit of the most favorable application of electrical apparatus. A successful gold dredge is primarily designed to make money. Electric drive is merely an incident in the process, so that, while it is unquestionably often advantageous to modify the ordinary dredge design so as better to accommodate it to the characteristics of the electric drive, nevertheless the fact should not be lost sight of that the electric drive is simply an incident to effect economy and that other considerations are often of greater importance than the most advantageous installation of a particular type of motor in a particular manner.

In considering how electric drive can help the dredge make money, the following factors enter into the total charge against the electric plant:

1. Interest on investment; which is affected by the first cost of any particular arrangement.

2. Power charges; which are affected by the efficiency of the motors and the system of control.

3. Maintenance charges; which are affected by the type of apparatus chosen.

4. Delay charges; which may be very seriously affected by proper or improper application.

As stated above, the gold-saving end of a dredge does not offer any particularly great problems in the application of electric drive. A motor is required to drive either a shaking or revolving screen which removes the coarse rock from the finer gold-bearing sands and gravel. This motor may be either geared or belted to the screen. Gearing is preferable on account of its saving in space, but belt drive is preferable as far as the motor is concerned, on account of the damping effect upon the vibration incident to the screening operations. Squirrel-cage motors are generally used for this purpose and are entirely successful, but some designers advocate motors with phase-wound secondaries in order to reduce the strain at starting. The writer is inclined to favor the squirrel-cage motor on account of its freedom from details which may increase the maintenance charge.

All of the gravel and sand which passes through the screen must be washed in order to obtain the gold out of it, and for this purpose a very considerable volume of water must be pumped

on the bridge. Centrifugal pumps are usually used on account of the low head and large volume to be handled, and these are best driven by direct-connected squirrel cage motors. Apart from those features which tend to reduce the maintenance charge, such as adequate insulation, adequate air gap, and adequate bearings, the efficiency of these pump motors deserves consideration, as the amount of the total power used by the dredge used for pumping is very considerable, usually as high as 40 per cent, and sometimes higher.

The tailings, or refuse matter that is sorted out by the screen, must be removed to some distance from the hull of the dredge so that it will not pile up under the hull and strand the dredge. Two methods of taking care of this matter are in use. One, the less common, is to pass the waste down a chute, helping its progress with a stream of water. The other and by far the more common method is to employ a belt conveyer running out of the back end of the dredge for a distance of 90 ft. (27.4 m.) or more, which conveyer is commonly referred to in dredge practise as a "stacker". This stacker is motor-driven. The application is reasonably severe owing to the fact that the motor is usually at the far end of the stacker and, therefore, often exposed to the weather, and also due to the fact that when the stacker has been at rest, considerable torque is required to start it loaded. In cold climates, a stacker when at rest is often apt to freeze, due to the moisture contained in the waste being carried by it. Starting under these conditions is particularly arduous and in some places this trouble is overcome by putting the stacker in a continuous canvas tent like a tunnel and passing steam pipes from a little low-pressure heating boiler up inside this tent. This again makes life hard for the motor because moisture vaporized by the heat of the steam pipes rises to the far end of the stacker where the motor is located, and there often condenses on the motor whenever that machine is shut down and allowed to cool. Accordingly, a motor for stacker service should primarily be designed with adequate insulation to resist continued moisture, and in some cases drip guards have advantageously been placed over the ventilating openings in the motor. Squirrel cage motors with heavy torque characteristics have been used successfully for stacker drive, but the general tendency is to use motors with phase-wound rotors in order to obtain a good starting torque. Here again is the question whether complications of a phase-wound motor are justifiable, and in the writer's opinion it is

probably preferable to use a squirrel cage motor designed for good torque characteristics, with possibly a trifle more resistance in the secondary circuit than is found in standard squirrel cage induction motors. A stacker motor is comparatively small as compared with the total motor installation on the dredge, and a slight loss in efficiency on such a small unit is more than offset by a saving in maintenance.

The application of electric power to that portion of the mechanism used for digging is a much greater problem than anything met with in connection with the other applications on the dredge.

There are three distinct types of gold dredges using entirely different digging mechanisms: (a) dipper dredges, (b) suction dredges, and (c) elevator dredges.

(a) The dipper dredge uses a boom and scoop almost exactly like a steam shovel. It is now practically obsolete in the gold dredging industry because of its poor power economy and because the dipper is actually digging dirt during a very small portion of the time that it is in operation. In other words, too much time is lost in lifting the loaded dipper, dumping it, and returning it to the digging position.

(b) The suction dredge is very similar to the ordinary dredges used in harbor and waterways excavations. Its digging end consists essentially of a large centrifugal pump suitable for handling semi-solid material, and is driven by a direct-connected varying-speed induction motor. The suction dredge is applicable for gold mining only in those few localities where water is very abundant and where the gold is found in loose sand. Its application to the gold mining industry is so limited that its details will not be discussed in this paper. It has the particular advantage, however, that its operation is continuous.

(c) The elevator dredge is the most commonly used for gold mining. It is essentially a continuously operating dipper dredge, combining all of the advantages of the steam shovel with the continuity of the suction dredge. A chain of scoops, or "buckets" as they are called, runs over a boom or "ladder," as it is commonly termed. This boom or ladder is swung from a gallows frame or derrick, and by properly manipulating the cables that control it, the boom is held up against the bank to be dug, and the bucket chain driven by a motor, so that each bucket scoops up its fill of earth as it comes round the end of the boom and carries its load without interruption to the mouth of the screen described

above Fig. 1 shows the essential parts of an elevator gold dredge as described above. The illustrations on Plate CXIV show some typical elevator dredges and show very clearly the boom, the bucket chain, and the gallows frame from which it is suspended.

Power is required at the digging end primarily for driving the bucket chain, but some power is also required for lifting and lowering the ladder and for operating the devices that pull or hold the dredge up against the bank so that the buckets will bite into their work. Ordinary winches similar to those often used on sea-going vessels are used for these purposes. The duty of the motors is entirely akin to ordinary hoisting service and of very intermittent nature. An intermittent rated wound-rotor motor with high torque characteristics is successfully used.

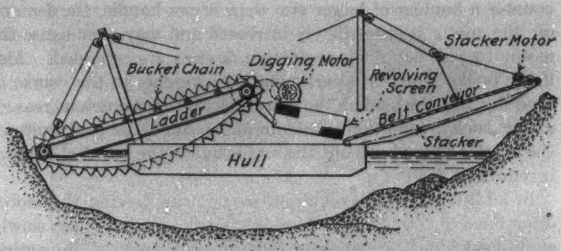


FIG. 1—ESSENTIAL MECHANISM OF AN ELEVATOR-TYPE GOLD DREDGE

The drive of the bucket chain is the real problem on the dredge and no system that has ever yet been devised has proved itself entirely free from all objections. For one thing, power requirements are at times very excessive and vary through a wide range. Accurate speed control is also essential. Good economy is of importance on account of the comparative size of the digging motor compared with the rest of the installation (in this connection it might be stated that the digging notor is usually from 35 per cent to 45 per cent of the total motor capacity on the dredge). Greatest of all is the problem of adequate and successful mechanical connection between the motor itself and the bucket chain.

The power requirements for driving the bucket chain under ordinary conditions may be calculated reasonably closely when the size of buckets, the number of buckets handled per minute,

and the type of ground to be dug, are taken into consideration. The following table gives some fairly typical test results:

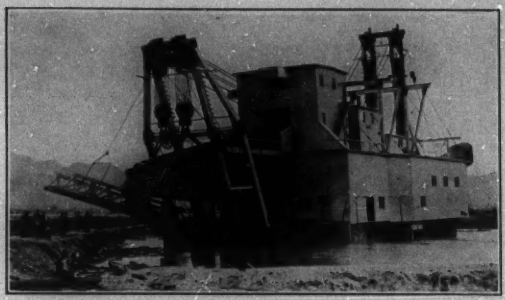
Place	Size of buckets cu. ft.	Buckets per minute	Motor rating h. p.	Average h.p. input
Oroville	5	18	75	65
Marysville	7	20	150	140
Marysville	7½	19	200	155
Conrey	9	18	150	185
Natoma	14	21	400	285
Folsom	13½	20	300	202
Boston & Idaho	15	..	300	285 (?)
Conrey	17	22½	550	460

N. B. All close-connected chains,—ordinary digging.

However, should one of the buckets in a bucket chain encounter a boulder of larger size than it can handle, the demand on the motor is immediately increased and may even cause the motor to pull out if no protective devices are provided. Also if the buckets run into particularly sticky clay in the course of their digging, the load on the motor may be very much increased, and as such a condition is seldom momentary, the continuity of the overload may burn out the motor unless the speed of digging is reduced.

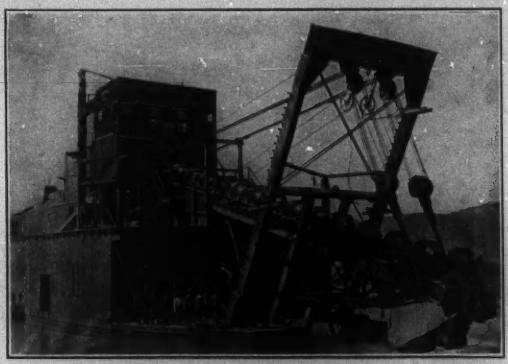
In addition to these requirements, during digging the motor drive must also be capable of revolving the bucket chain slowly at no load for the purpose of repairing the buckets, inspecting the chain, and similar work required for the purpose of mechanical maintenance.

The bucket chain is driven through a hexagonal spindle at the top of the ladder, over which spindle the buckets pass. Each one of the flat sides of this spindle or "tumbler" as it is termed, engages with a corresponding flat side on the under side of the bucket, and the drive is accordingly a positive drive just l ke any chain drive would be. If the tumbler turns, the bucket chain has got to move or break. It cannot slip. An adequate and successful method of transmitting power from the driving motor to the tumbler has been the source of considerable study by dredge designers the world over. The tumbler shaft usually carries two pinions, one on each side, which engage with two gear wheels carried on a common shaft. This shaft is connected through an adjustable slipping friction to another drive shaft by means of gearing, and the motor drives the last-named shaft. It may be either belted or geared to this shaft. Belting the



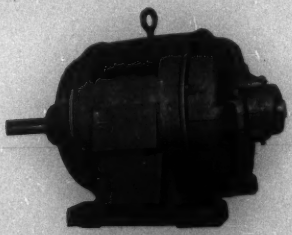
DREDGE WITH 17-CU. FT. BUCKETS. [ROSENBLATT]

Chain is "close-connected", *i.e.* each link of the chain is a bucket. 500-h.p. digging motor and liquid rheostat control; cooling system for electrolyte is visible, dipping into pond at side of dredge.



DREDGE WITH 12-CU. FT. BUCKETS. [ROSENBLATT]

This shows clearly the ladder and the bucket chain. The chain is of the type known as "open-connected", in that there is a link without a bucket between each two buckets.



[ROSENBLATT]

TYPICAL SQUIRREL-CAGE MOTOR, WITH SPLASH-PROOF COVERS, FOR STACKER DRIVE.

motor is of course the easier on the electrical apparatus, but on the other hand has certain disadvantages. A very large and expensive belt is required on account of the tremendous torques involved. There are sometimes difficulties due to maintenance, because of the moisture that is often present on board a dredge. The belt sometimes slips just when maximum torque is wanted. Occasionally, under the heavy stress due to the slipping friction having rusted, a belt will break. Also a belt transmission for the transmission of the torques involved takes up considerable space, and space on a dredge is valuable.

On the other hand, gearing, while economical in space and entirely positive in action, has the disadvantage that it imposes very severe service on the electrical equipment, in that every strain and every vibration from the bucket chain finds its way back to the revolving part of the motor. Flexible couplings have been tried between the motor and the driving gear but without success. The large variations in torque met with, sooner or later ruin any type of flexible coupling that has as yet been tried. The gear drive has, however, proved entirely successful where a motor has been secured that will adequately withstand the stresses. Of the two methods, belt vs. gear drive, each has its ardent devotees.

From a consideration of the above, it will be seen that the motor required for digging service on an elevator dredge must have the following characteristics:

(a) It must be varying-speed machine; and if in addition it can be made an adjustable-speed machine this would be a considerable advantage.

(b) It must be capable of being revolved at light loads and very low speeds.

(c) It must be capable of developing a maximum torque, at any speed from zero to approximately full load speed, of several times its normal rated torque.

(d) It must be capable of carrying for prolonged periods of hard digging a torque overload of approximately 25 per cent at a speed reduction of probably 25 per cent.

(e) It must be of substantial mechanical construction, particularly as to shaft and bearings, in order to resist a very heavy belt pull when belt drive is used, or repeated shocks of severe gear thrusts when gear drive is used.

(f) It must be reasonably efficient.

In order to obtain all of the above characteristics, it has often been suggested that a direct-current motor of the type used in

steel mills, with possibly variable-voltage speed control, might prove advantageous for digging service on big gold dredges. However, every investigation that has been made (to the writer's knowledge) of this matter has developed the fact that the losses in efficiency due to the conversion from alternating current to direct current practically offset the advantages gained by more flexible control under the ordinary cycle of operation, and further, the first cost of such an installation is prohibitive, considering the ordinary life of a dredging venture. In this connection it might be stated that while there are exceptions, the average dredge is about worn out at the end of ten years, and will then require either complete rebuilding and remodeling or will operate with so many shut-downs due to breakages and the like that rebuilding or scrapping will prove most economical. Accordingly any installation more expensive than ordinary must show a saving that will repay the extraordinary expense in 10 years, and this no combination of direct-current equipment has as yet been able to show.

Accordingly the only type of motor left available is the moderate-speed wound-rotor induction type, and for the most successful application the motor should be designed with special reference to the work it has to do.

From experience with the troubles of a dozen dredges, large and small, the writer would recommend specifications embodying the following:

(1) The motor should be capable of carrying its rated load continuously with a rise not to exceed 40 deg. in any part.

(2) The motor should be capable of developing a torque 25 per cent in excess of its rated full load torque at a speed of 75 per cent of its synchronous speed for a period of two hours with a rise not to exceed 55 deg.

(3) The motor should have a maximum torque and a starting torque of not less than 2 1/2 times its full-load torque.

(4) The shaft shall be of such material and dimensions that strains due to the developing of maximum torque shall not appreciably affect the dimensions of the air gap on any side of the motor.

(5) The bearings shall be designed to resist an upward thrust, and shall preferably be of the design known as rolling-mill bearings, furnished with stud bolts and lock nuts instead of the usual design employing cap screws.

(6) The lubrication of the bearings shall be adequate. On motors of 200 h.p. and over, at least two oil rings per motor

bearing are recommended. On motors of 500 h.p. and over, the use of gravity feed lubrication should be considered.

The problem of control of large motors used for digging service on gold dredges would be more simple if direct-current motors could economically be used. As, however, their use is impractical, the control for a-c. motors that most nearly approaches direct-current control is desirable. The control must permit reversing the direction of the motor, principally to permit the bucket line being backed away from obstructions. For service during the repair of the bucket line, small variations in speed should be obtainable, particularly at partial loads. A control permitting continued running at low-speed points is particularly necessary.

For small motors on little dredges, say employing a digging motor of 100 h.p. or less, the ordinary drum-type controller proves adequate. For larger installations a combination of magnet switches controlled by a master controller has been used in a large number of installations, but for the larger motors the ideal control seems to be the liquid rheostat.

Magnet-switch control has been used satisfactorily on a considerable number of dredges employing digging motors as large as 400 h.p. The very large fleet of large dredges operated in California by the Natoma Consolidated mostly employ magnet-switch control on dredges having digging motors of 300 h.p. and larger. It has, however, several distinct disadvantages for dredge service. The principal disadvantage is that only a limited number of definite points is available with this type of control unless the number of magnet switches in the secondary circuit is made very large, which in turn makes the controller inordinately expensive. Therefore, small variations in speed, particularly at light loads, are not available with this type of control, and in order to obtain slow movement of the bucket chain, it is customary to start the motor up and then plug it, with consequent strain on all mechanical parts, as well as wear on the control contacts. Further, this type of control does not allow the dredge operator to pick out any particular speed at which he desires to run. He can only pick a particular point on the controller and the corresponding motor speed will depend on the torque being exerted by the motor.

Another disadvantage of this type of control is the tremendous amount of resistance required for a large motor, as the resistance must be sufficient in amount to permit very low motor speeds at light loads, and large enough in capacity to permit continuous

operation at reduced speeds with heavy torques. This makes a very bulky resistance and unless the resistance is large enough there is considerable danger of the overheating of the grids starting a conflagration.

The liquid rheostat for digging motor control has, on the other hand, none of the disadvantages of the magnetic switch control. There are no definite steps, and the speed of the motor may be varied by infinite gradations. The operator simply moves the rheostat handle until he obtains the speed he desires. In other words, he does not work for any particular point on the rheostat, but works simply with the idea of getting the speed he wants. For large motors, the liquid rheostat and its accessories take up much less room than would a corresponding magnetic switch control and its attendant resistance, and there is never any danger of the electrolyte used (water and common washing soda) causing a conflagration.

However, the liquid rheostat for use on dredges must be modified from the forms cominonly used for hoist service and the like on land. The first liquid rheostat installed on dredge service was on one of the Natoma dredges with a 400-h.p. motor, and while it was operative, it was not entirely satisfactory, because certain essential details of design and application were overlooked. A very similar liquid rheostat on which these details have been given due attention is now being used on one of the dredges of the Conrey Placer Mining Co., and has been entirely successful and satisfactory in operation with a 550-h.p. digging motor, which I believe is the largest digging motor on any elevator type gold dredge in operation today anywhere.

In order to keep down the size of the liquid rheostat for this work, it is practically necessary to provide some means of artificial cooling for the electrolyte. Usually this is accomplished by circulating cooling water through coils in the rheostat tank. On the Natoma rheostat the mistake was made of pumping water from the pond in which the dredge floats, through these cooling coils. Due to the operation of the dredge this pond water is usually pretty muddy, and often carries a large percentage of solids in the shape of silt. At Natoma this silt coated the inside of the cooling pipes, thus reducing their effectiveness and eventually clogging them up, necessitating a shut-down while they were blown out with compressed air. Shut-downs on a dredge cost money, because to realize the greatest return on the investment, the dredge must be digging all the time. Therefore this eature made the Natoma rheostat undesirable. At the

Conrey Placer Mining Company's property, the cooling system consists of a series of pipe coils immersed in the pond, and the electrolyte is pumped from the rheostat tank through the coils and back again, instead of pumping pond water up to the tank and through coils installed therein. There has never been a shut-down on the Conrey dredge due to the rheostat or its cooling system. The motion of the dredge in the pond is sufficient to keep silt from settling on the cooling coils.

Another point that was overlooked on the Natoma installation was the fact that dredges swing, and often rock considerably. This causes the electrolyte to splash out of the rheostat. Usually such loss by splashing was replaced by pouring in additional water, but this of course changed the density of the electrolyte and caused the operators some trouble. On the Conrey rheostat baffle plates and enclosing covers were supplied, which effectually prevented any splash.

Another trouble that was experienced at Natoma was that, due to deficiencies in the cooling system mentioned above, the electrolyte very often attained a very high temperature during hard work, which caused excessive evaporation. Under certain conditions this evaporation was so great that the annoyance and expense of bringing the amount of fresh replacing water required on to the dredge and filling the rheostat was considerable. This trouble has been obviated at the Conrey installation by having an adequate cooling system.

All in all, it may be said that for large digging motors of say 350 h.p. and up, the liquid rheostat makes an ideal method of control, provided the rheostat is of adequate mechanical construction for the service and is provided with a proper and sufficient cooling system. Both liquid rheostat and magnet switch control may be arranged to give the same advantages as to protection against acceleration at too high a rate and against excessive overload due to sudden changes in speed.

It will probably be gathered from the above remarks that the successful application of electrical apparatus to gold dredging operations depends on a multiplicity of details, each of which may be of comparatively minor importance in itself, and this is true. With the areas that are now still available for dredging, a multitude of small economies must be practised in order to make the process commercially successful. When it is considered that many dredges dig for about four to five cents per cu. yd. and that the gold contents of the ground often run as low as seven cents per cu. yd., it can readily be seen that a matter of one cent econ-

omy or waste may make or break the concern doing the dredging. Therefore maintenance deserves consideration. But most of all, freedom from shut-downs is of prime importance. The dredge cannot make any money while it is not digging; but, interest, not only on the money invested in the dredge, but on the money invested in the purchase price of the land that is being dredged, goes on just the same, and therefore shut-downs must be avoided at any reasonable cost, and this should be particularly borne in mind in the selection and application of the electrical apparatus and its control.

A digging motor that may be of sufficient capacity, but cannot be adequately controlled, may break a bucket chain and put the dredge out of business for 24 hours. Ordinarily, dredge operators figure on operating 24 hours a day 365 days a year and a fair average is to expect the dredge to be actually performing its operations for 85 per cent of the total time.

On account of the high load factor, and on account of the comparative uniformity of a large percentage of the load, as well as on account of the comparatively large blocks in which the power is purchased, dredges make a particularly attractive load for hydro-electric central stations, and a few figures as to the power consumption of dredges may be of interest in this connection.

Moderate-size dredges with buckets of about 5 to 7.5 cu. ft. capacity will handle from 60,000 to 100,000 yards per month, at a power consumption from $1\frac{1}{4}$ to $1\frac{3}{4}$ kw-hr. per cu. yd.

Larger dredges with buckets up to 15 cu. ft. capacity will dig from 125,000 to 250,000 cu. yd. per month, and will take from 1 to 1 1/2 kw-hr. per cu. yd.

The very large dredge of the Conrey Placer Mining Co. mentioned above, which has buckets of 17 cu. ft. capacity (I believe the largest in the world) has handled 520 cu. yd. of material per running hour. Including delays, this means 325,000 cu. yd. per month. Handling material (heavier than usual) weighing 3000 lb. per cu. yd., its power consumption was 1.28 kw-hr. per cu. yd.

The above figures are total power taken by the dredge for all purposes. The power taken by the digging motor is about 40 per cent, on an all-day average, of the total power. From such test results as are available, the power for digging seems about proportional to the yardage dug, *i. e.*, the kilowatt-hours are proportional to the yardage handled times the number of hours during which it was dug.

DISCUSSION ON "APPLICATION OF ELECTRIC MOTORS TO GOLD DREDGES" (ROSENBLATT), SPOKANE, WASH., SEPTEMBER 11, 1914.

Ford W. Harris: The problems so clearly defined by Mr. Rosenblatt are, in general, those that confront any engineer proposing to equip rough heavy-duty machinery with motors. As electrical engineers we are in duty bound to give electric power the benefit of every doubt when the expediency of a given installation is considered, but that the application of motors to dredges, shovels, and the like, is a hard problem must be understood at the outset. It is primarily a problem of applying a constant speed, constant maximum torque motor, to a variable speed, variable torque load. More particularly it is the application of a constant torque driving means to a variable torque load. We have the problem of a widely variable load that must be economically handled regardless of the speed. The operator wishes to operate the major portion of the time at constant speed with a fairly uniform load. At times this load is enormously increased and at times he desires to greatly reduce the speed for repairs, etc. In general, as far as satisfactory operation is concerned, the enormous pulls occasionally needed may be and preferably should be exerted at a low speed, so that the actual power requirements may be fairly constant.

Obviously what is needed is means for connecting the load and the motor in variable speed ratio, the problem being very similar to that solved by the change gears of an automobile. Obviously, also, no such mechanical means has been devised which will handle the very variable shocks and strains incident to transmitting 500 h.p. to such a load.

The method by which Mr. Rosenblatt has solved the dredging problem is open to certain very obvious objections. Speed control by liquid rheostats involves at the outset large energy losses, the rheostat being primarily designed for such large losses. Motors having the mechanical and electrical characteristics outlined are expensive and heavy. It should be remembered that when a wound-rotor motor has its speed reduced by the insertion of external resistance there is no increase of torque but merely a decrease of speed. The power output of the motor is reduced with the speed. This is only a partial solution of the problem.

I have personally figured many installations of large and small motors for hoists, shovels, and the like, and I believe that a serious mistake is made in applying a-c. motors to work of this kind. Particularly I think that the application of the a-c. motors of any kind to digging service on a dredge is poor engineering. Here you need a moderate torque at a high speed and a much larger torque at a correspondingly reduced speed. The larger companies have made many installations of a-c. motors for such service and made them stick, but it is significant that most large mine hoists are operated by d-c. motors,

through the Illgner system, and that our street cars still run largely with d-c. motors in spite of persistent efforts to enlarge the number of single-phase installations. It is further to be noted that the single-phase railway motor has series motor characteristics, and that few installations of induction-motor-driven railways have ever been seriously attempted in this country. If it is not feasible to operate a railway car, which is an approximately constant load at variable speed, with induction motors, how much more hopeless it is to operate a gold digger which requires large torques at times when the speed may be reduced to keep the power input fairly constant.

To my mind there is no good way to drive such a load from a constant-torque motor. The load is one that requires series motor characteristics. If there were available single-phase series motors which could be bought at a reasonable price and maintained at a reasonable cost they might be used in this connection. Barring such motors the proper system would be the application of a double or quadruple equipment of series d-c. motors in combination with a d-c. generator—a-c. motor set.

With such a multiple motor drive and proper series-parallel control it would be possible to operate on a variable torque basis and get fine results, the motors running four in multiple under normal conditions and being thrown in series for heavy pull-outs at low speeds. The power economy would be high and with proper cut-outs on each motor the reliability factor would be increased, as three motors could be used to operate in an emergency. While the first cost of the motor equipment would be high, the greater flexibility and reliability of the equipment would result in greater output at the dredge, which would soon wipe out the additional investment.

M. H. Gerry, Jr.: I am glad to say a word on this paper because there is much of interest in connection with such a machine as a gold dredge. This paper is a further demonstration of the great flexibility of electrical power and the wide diversity of its application. I disagree with the statement made by some one in the discussion, that there is any difficult principle involved in this application of electrical power. The problem is to ascertain in advance, the actual conditions of operation, and in this respect it does not differ from electrical traction or the thousand and one other applications of electrical power. Once these conditions are fully understood, the difficulties very largely disappear and are then only those quite commonly met with in solving mechanical and electrical engineering problems. However, it requires much study and time to analyze a problem of this kind, and it is here that the skill of the engineer is required.

It has been my good fortune to have some connection, in an engineering way, with the dredges which form the subject of Mr. Rosenblatt's paper. I was familiar with the situation from the first, when the dredges then in operation were driven

by steam engines. These older dredges have all been rebuilt and are now operated by electrical power, but the dredge which forms the special subject of Mr. Rosenblatt's paper, is a later installation and was designed originally for electrical operation. The problem at first presented was that of the general advisability of applying elecrical power to the operation of dredges in this situation, and it was a question on which engineers differed. The ground was hard, there were many large boulders and the bedrock was at great depth. The steam dredges were experiencing much difficulty, and the power was insufficient for the work and there were constant breakdowns and delays. A very able engineer who was called into consultation, was of the opinion that the conditions were altogether too difficult to permit of operation by electrical motors. The ever-varying pull on the digging chain, the frequent obstructions met with in the way of boulders and other causes, tended to produce enormous strains and varying torque on the driving motor, and render questionable the successful operation by electrical power. Those who have seen a dredge of this kind operating in hard ground will appreciate how difficult the problem appeared at that time. One engineer observing the operations, used this expression, "see it toil, see it toil;" the inference being that the "toil" was altogether too strenuous to be undertaken by an electrical drive. That, however, is now all history, and we know that for any dredging service, no matter how difficult, electrical motors properly designed are altogether suitable. The dredge is a comparatively simple machine; as here applied it is a combination of elevator and excavator. At times there is very little actual digging, as the earth is loose and falls into the buckets. Under these conditions it is merely a question of elevating this earth to the surface. As the excavation reaches bedrock the conditions change; the material is hard and tough and must be torn apart with the expenditure of a considerable amount of energy. From my knowledge of conditions at Ruby and elsewhere, I would say that the dredge operations for the machine described by Mr. Rosenblatt, are the most difficult in this country. This hard digging, the great size of the dredge and the depth from which the material was excavated, were the conditions surrounding the problem for this particular dredge. The bucket chain is a massive affair and it moves at a slow rate of speed. The pull on the bucket chain is constantly varying, due to the ever-changing conditions of digging, and also to the further fact that the chain is driven from the top by a five-sided tumbler, resulting in a constantly varying driving radius. The motor torque is, therefore, ever changing and may vary widely during short intervals of time.

One of the important conditions of dredge operations is to maintain maximum speed of the digging chain in the upper part of the excavation and to be in readiness to develop maximum pull on the chain, at somewhat lower speed, as soon as bedrock

is reached and the difficult ground encountered. It follows, therefore, that a considerable measure of speed control is absolutely necessary for successful operation in this situation. Many methods of obtaining this speed control have been suggested and applied, but the one described by Mr. Rosenblatt has proved eminently successful for conditions met in actual service. Some engineers have suggested a change to a direct-current drive, but I have never been able to obtain any better efficiency or improved performance for direct current, where the available source of power was alternating current, and the necessity existed, therefore, of using conversion apparatus. At the present time there is nothing better or more available for this service than an alternating-current motor having a wound secondary with a control rheostat capable of continuous operation.

Mr. Rosenblatt has well said that for the best results it is necessary to keep these dredges in as continuous operation as possible. When the records show that month in and month out the dredges have been in service 80 per cent of the total time, it is certainly a creditable performance. Such results as this prove that electrical power, when applied to dredge operations, is a great success, and that the apparatus as described by Mr. Rosenblatt has materially contributed to this result.

Some discussion has arisen in reference to the relative merits of a belt drive as compared with a direct gear drive for the main bucket chain of a dredge. This is a question more of expediency and economy than of performance. It is not well to make the drive too rigid, and some means of providing for a little slip in case the buckets come up against a rigid obstruction, is very desirable. With a small or moderate-size dredge, this result can be obtained in a rather inexpensive way by using a belt drive from the motor and permitting the belt to slip if occasion should arise. On very large dredges, however, belts are too bulky and are very objectionable for mechanical reasons, and it is better to provide a gear drive with a form of mechanical slipping friction introduced at some point between the motor and the bucket chain. This slipping friction should be designed, not as an ordinary friction clutch, but as an actual slipping friction.

To return to the matter of control for the main digging motor, and referring especially to the liquid rheostat described by Mr. Rosenblatt, I would like to add that this has proved to be a most satisfactory piece of apparatus. For hours at a time the motor is operated at reduced speed and the heat developed in the rheostat is taken care of very nicely by the cooling coils. The regulation is excellent and the man operating the dredge has fine control over the bucket chain. For motors on small dredges, almost any kind of rheostat will work well, but for such an immense dredge as the one here described, I know of no better arrangement than the liquid rheostat. The arrangement

whereby the cooling coils are placed on the outside of the boat in the dredge pond, is worthy of special attention. This device has obviated all the trouble with the circulation of muddy water through cooling coils immersed in the rheostat tank, and is one of the reasons for the success of this installation.

In conclusion I would like to emphasize the thought which I first mentioned; that it is not at all difficult to apply electrical power or electrical methods to the operation of any machinery if the conditions be carefully analyzed in advance, and the proper use be made of methods and machinery now well understood.

F. A. Ross: I am conscious that a mining engineer can take but small part in this discussion of Mr. Rosenblatt's paper. The word "mining" can scarcely be applied to gold-dredging since, as Mr. Gerry has said, dredging is but the elevation of gold-bearing gravels and a transfer of the same to another point; therefore, the design and operation of dredges comes within the province of the mechanical, electrical and, often, the hydraulic engineer, rather than in that of the mining and metallurgical engineer. The latter is called into the question only at the beginning and at the end. Because of his training in estimating the value of mineral-bearing ground he does the drilling or sinks the test-pits and then he estimates the profits possible, or probable, from a handling of the greatest tonnage practicable.

At this point he must turn for help to the mechanical engineering departments of the dredge-builders, where the data he submits govern the design of the dredge; and the mechanical engineer, himself, must apply to the electrical engineer for motor designs and for advice as to the general application of electricity to the needs of the case in hand. But the mining engineer must make no mistake as to the average character of the gravel to be worked nor may he fail to note the heaviest duty that the dredge must perform. Moreover, as a metallurgist he must specify the type of gold-saving apparatus to be used, but, once the machine is built and at work, he may safely step aside and leave its operation to the skilled dredge-crew that takes orders henceforth from the mechanical and electrical engineers. Electricity has so far superseded steam as a motive power in dredging that there are few steam dredges employed today in working gold-bearing gravels.

As Mr. Gerry said, the latest gold-dredges are mechanical monsters, performing feats of strength and endurance that are almost unbelievable by those that see them for the first time; and they call for a refinement of theory and practise both in mechanical and in electrical design. The close-connected buckets must tear away at consolidated beds of boulder-gravel without pausing and must work out of sight, under water, at depths of 70 feet or more. Gravels differ greatly in character, some being composed of small, nearly uniform, boulders, while others contain boulders of all sizes, even up to a size that renders dredging impossible.

The greatest difficulty, then, lies not so much in the building of a machine strong enough to stand up to the duty imposed upon it, as in an accurate determination of the total work to be done and the character of that work. Mr. Rosenblatt mentions a maximum capacity of about 250,000 cu. yd. per month for the largest gold dredges, but there is one up in Idaho Basin which, according to the statement of its general manager, made a record of 340,000 cu. yd. in one exceptionally good month. In this case, the gravel is small and uniform and the beds shallow.

L. K. Armstrong: After what Mr. Ross has said I don't think it will be necessary for me to say anything or to apologize for the little the mining engineer knows about gold dredges.

I have in mind the early days when the electrical engineer was seeking a market for his current. Some of them conceived that they might apply it to the gold dredge business, and after a considerable time and many attempts they seem finally to have acquainted themselves so thoroughly with the business that the business has been practically turned over to them.

I was trying to think, while one of the speakers was talking, about a meeting of the American Institute of Mining Engineers, when this particular subject was brought up and there was a lot of discussion on the question of whether or not electricity could ever be applied successfully to the operation of a gold dredge; the discussion was all in favor of the negative. Today from the information we have here, I find that gold dredging would be practically unsuccessful, and I am very certain that is so in many cases, but for the application and practical developments on the part of electric engineers and the application of electrical power.

W. M. Shepard: In regard to the case of squirrel-cage vs. slip-ring motors for screen and stacker drive. All of the earlier California dredges were equipped with squirrel-cage motors and it is only on the larger dredges built in the last few years that slip-ring motors have been used.

On large dredges the screen represents quite a heavy starting load, especially if it is started when full of wet clay and rocks, which very often happens. The screen is operated continuously when the dredge is in operation, so that the characteristics desired are good efficiency and high starting torque.

On large dredges for deep digging, the stacker is very long and elevates the material to a considerable height; this is necessary to get the large amount of material handled out of the way. On the Yuba Consolidated Goldfields dredge No. 14, which digs to a depth of 70 ft. below the water line, the stacker is 137 ft. long. Starting a stacker of this kind, especially if it happens to be loaded, as is frequently the case, requires a high starting torque and it sometimes takes several minutes to bring it up to speed.

If a stacker of this kind was operated by a squirrel cage motor of ordinary design it would require a larger motor than if the slip-ring type was used, on account of the lower starting torque.

A squirrel-cage motor with high-resistance rotor could be used which would give the required starting torque, but at the sacrifice of efficiency, and as these motors are large size, those on some of the larger dredges being 75 h.p., and operate at all times that the dredge is running, this loss in power even at a low rate would become quite an item. With some dredges where a considerable number of small boulders are handled over the stacker, the speed has to be reduced at times when a number of these are being handled, as, if the speed is too high, the boulders will not stick to the stacker belt and be carried over the top, but will roll down and cause considerable trouble. A slip-ring motor with proper resistance would take care of a case of this kind when a squirrel-cage motor would prove unsatisfactory.

The difference in maintenance cost between the slip-ring and the squirrel-cage motors used on these drives is shown on actual operation to be negligible; for the slip-ring motors occasional extra brushes are required, and for the squirrel cage, extra contacts for the starters.

The drum-type controllers used with these motors give practically no trouble as the service required of them is comparatively light.

Regarding Mr. Rosenblatt's recommendations covering specifications for the digging motor: it seems to me that the introduction of the special features which he recommends is confusing and not to the advantage of the purchaser. For instance, a motor designed to meet the standard heating guarantees adopted by all American motor manufacturers from the A. I. E. E. Rules would, in all probability, meet the specifications submitted by Mr. Rosenblatt and the use of standard specifications would be of advantage to both the purchaser and manufacturer. Furthermore, it is not usually necessary for the digging motor to run for considerable periods at reduced speeds. The rate of digging can be controlled either by changing the speed of the bucket line (varying the speed of the digging motor) or by varying the rate of feed, which is controlled by the swing winch.

The dredge has side lines on either side connected to deadmen on the bank. The swing winch in connection with these lines swings the dredge back and forth across the face of the cut while the bucket line is in operation. The rate at which the dredge is swinging governs the feed of the buckets and so the amount of material moved and the load on the digging motor.

It is much more efficient to allow the digging motor to operate at full speed with all resistance cut out of the secondary and control the load by means of the swing winch motor (which is from 10 per cent to 15 per cent of the capacity of the digging motor), than to operate the digging motor at reduced speed with consequent losses in the secondary resistance.

In regard to special bearings in the digging motor to resist upward thrusts, the large majority of gold dredges have the

digging motors belted, which requires no special features in the bearings. The larger motors are usually provided with three bearings.

Regarding those motors which are geared: the bearing thrust when digging should be downward; the only times when the bearing thrust should be upward would be when the bucket line was being backed up, which would be only a very small fraction of the time it was going ahead, and when it was being backed up the load would be light, as there would be no digging.

The point which I wish to bring out is that standard equipment, if properly applied, is well adapted to meet all conditions of dredge service. I have had to do with the electrical equipment of something over thirty gold dredges of bucket capacities ranging from 3 to 18.2 cu. ft. and digging depths of from 15 to 70 feet. These dredges operate in every character of ground and all use standard equipment. Among them are some of the most successful dredges yet constructed. The problem in electric drive is in proper application and not special equipment.

Regarding the control of the digging motor, I believe that proper drum-type controllers are all that is required for motors up to 200 h.p. capacity. There are quite a number of digging motors of this size operating with drum controllers and they have proved entirely satisfactory. A number of them have been in operation over a period of years. The control is adequate and simple and the maintenance cost very low.

Drum-type control has been employed on digging motors as large as 300 h.p., but in the writer's opinion better service could be obtained with other types of control for motors above 200 h.p.

For larger motors magnetic control or properly designed liquid rheostats can be used. There are a number of magnetic control equipments in successful operation on digging motors of 300 h.p. and 400 h.p. capacity, some of which have been in operation for two or three years. They have all proved satisfactory in operation and their maintenance cost has been low.

While experience with liquid rheostats on board dredges is as yet very limited, and there are some difficulties to be overcome, there is no reason why, with proper design, their operation should not be successful.

I cannot agree with Mr. Rosenblatt regarding the excessive amount of resistance required with magnetic control nor with his statement regarding the fire risk incident to the use of resistors. The digging motors are provided with standard heavy duty resistors good for continuous operation at a speed reduction of fifty per cent, and these have proved entirely adequate; and in no case that I have ever heard of has there been any question of fire risk from these grids and there need not be, if they are so located that the air can circulate freely about them.

There have been a number of fires on dredges caused by electrical troubles; these, however, have nearly all been due to

faulty installations of oil switches. As a result of these fires the Board of Fire Underwriters of the Pacific made a thorough investigation and issued a set of rules on "Standard Electrical and Fire Protection for Dredges." This set of rules is very thorough and in them no question is raised regarding the grids nor are special precautions required in their installation.

Mr. Rosenblatt mentions the use of intermittent-rated motors for ladder hoist winch, and for raising the spuds or controlling the head lines, if these are used instead of spuds; if separate motors are used for these purposes the intermittent-rated motor would be all that is necessary. As a rule, however, separate motors are not provided for this service. The ladder hoist winch is usually operated from the digging motor and this arrangement provides so much power that the ladder is raised much more quickly. The control of the spuds or head-lines is usually taken care of by the swing winch motor.

These operations are controlled by levers in the winch room. The swing winch is in operation all the time and an intermittent-rated motor is not suitable for this purpose.

The power required from the digging motor depends on the size of buckets, speed of buckets, depth of digging and character of ground dug. The size of buckets varies from 2½ to 18.2 cu. ft., the speed from 18 to 22 buckets per minute, the depth from 10 to 70 feet below the water-line, and the character of ground from loose gravel and sand to hard cemented gravel. The size and weight of a dredge does not depend simply on the size of the buckets, but is also governed by the depth of digging and character of ground.

The largest and heaviest gold dredge yet constructed is, I I believe, one of the all-steel California dredges which has 16-cu. ft. buckets and digs to a depth of 70 ft. below the water line. This dredge has handled 325,000 cu. yd. in a running month of 30 days. I believe the highest record for material moved is at present held by the Boston and Idaho dredge, which has buckets of 18.2 cu. ft. capacity and has a record of over 400,000 cu. yd. in one month.

In point of size and power this dredge is not the equal of the large California dredge just mentioned, but has shallower ground and easier digging.

A. A. Miller: I do not have anything in particular to add to the technical part of this discussion, but I know that a great deal of the work of this character, the use of electric power in gold dredging, is being carried on in the northern possession of our Canadian neighbors across the line, in the vicinity of Dawson, Yukon Territory, particularly; they have some of the largest gold dredges in the world, I believe, which are being used, particularly by Mr. Boyle of the Boyle Concessions; they have built water power plants and transmission systems of their own for the purpose of furnishing these dredges with electric power. Unfortunately the site of operation is so far removed from us

that we cannot get to them very frequently to know what they are doing, and the information apparently does not reach us. It would be interesting if we could get more detailed information from those particular dredges.

I believe there will be also in the course of the next year or so considerable activity in the vicinity of Nome in this same sort of work. I was told by a mining engineer who is familiar with conditions there that in the next two or three years there will be something like $5,000,000 taken out from a clearly defined area by dredging operations.

C. B. Rosenblatt: I am going to make this discussion as brief as possible, but there are a few things that I can't let go by. One of the gentlemen registered some objection to the use of alternating current. We all know that a direct-current motor would be an ideal drive. Nobody denies that; but the gentleman does not look at this matter from the dredging point of view, he looks at it purely from the electrical engineer's standpoint, and that is one thing I particularly ask you gentlemen not to do when it comes to dredging. Direct current for dredges has been figured over and over again. I believe Mr. Gerry here went into that as carefully as any man possibly could when the Conrey Placer Mining Company decided to electrify. Engineers in California went into it carefully too. It can't be figured out any way to show a monetary profit under conditions of power supply that obtain today—and remember the dredge is in business to make money.

Mr. Shepard has a very good communication from San Francisco. There is only one thing about it that demands comment and that is that it represents California practise as advocated by two manufacturing companies. Mr. Shepard's remarks apply particularly to the type of dredge built by those two companies, which use certain motor drives that are arranged primarily for the use of standard motors, even for the digging motors. There is considerable question as to whether the drives used by these manufacturers are the best for a big dredge, but that is not a problem for the electrical engineer to discuss. Mr. Shepard mentions particularly the use of a wound-rotor motor drive for the stacker as compared with the squirrel cage motor. That is a matter on which I said I expected some criticism from California because they have generally come to use the wound-rotor motor for that work. But remember the California climate is particularly favorable. It is all right to take a slip-ring motor and stick it up on the end of the stacker if you have a favorable climate and never get down below forty degrees above zero, but the conditions in Montana, Oregon, Wyoming and Alaska are different from that. Another thing Mr. Shepard does not take into account is the fact that the dredges with which he is concerned, have comparatively easy digging; while the Californians may not agree, I believe it is easier to dig the California gravel than it is the Northern clays, and Mr. Gerry brought that out

when he said that his own opinions and observations in this matter had been backed up by the observations of practical dredge men.

There are good points about each kind of drive. Each may be particularly fitted for a particular installation. There is no panacea for this dredge work. I have tried to point out the considerations that apply most generally. We have to analyze each case by itself and find the underlying conditions that make the selection of particular apparatus most desirable, and while unquestionably, for Mr. Shepard's own conditions, he has selected very excellent electric drives for those dredges in California, they will not necessarily work with best success everywhere in the world.

Presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Spokane, Wash., September 11, 1914.

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ECONOMY IN THE OPERATION OF 55,000-VOLT INSULATORS

BY M. T. CRAWFORD

ABSTRACT OF PAPER

The author gives a brief outline of the operating experiences on three 55,000-volt lines, two of which have been in service 10 years and one 5 years. The quality of the more modern porcelain insulators is notably superior to those first installed on these lines. A device is described by means of which defective insulators can be readily detected in the very early stages of deterioration, and by periodic use of this device and replacement of insulators, failures in service have been practically eliminated.

THE final measure of success in a transmission system is the cost of securing the desired performance therefrom. The failure of line insulators from breakage or electrical causes is a menace to service performance, and may be the cause of heavy maintenance expense if the failures are frequent and repairs must be made under emergency conditions.

The problem of securing satisfactory and economical operation from lines having gradually weakening insulators, has recently become an important one on some systems.

This paper outlines briefly the operating experience on several of the older lines of the Puget Sound Traction, Light and Power Company system, and describes methods employed to secure satisfactory performance economically.

GENERAL DATA

Nominal voltage, 55,000; non-grounded neutral; 60-cycle, three-phase current. All pin type insulators are of the design shown in Fig. 1.

Line A. In service 10 years, from Electron generating station to Tacoma. Length, 31 miles (49.8 km.). Number of insulators, 4450. Poles, 40-ft. (12-m.), set on average spans of 125 ft. (38 m.). Wires spaced six ft. (1.8 m.). No. 4/0 B. & S. copper 21 miles (33.7 km.); No. 0 B. & S. copper 10 miles (16 km.). Insulators cemented on iron pins. Wooden pins screwed in insulators were used on a portion of this line when

first installed, but have nearly all been replaced at this date with iron pins.

Line B. In service 10 years; from Electron generating station to Seattle. Length 47 miles (75.6 km.). Number of insulators 6850. Poles 40 ft. (12-m.), set on average spans of 125 ft. (38 m.). Wires spaced six ft. (1.8 m.). No. 4/0 B. & S. copper. Insulators cemented on iron pins.

Line C. In service five years at 55,000 volts; from Snoqualmie generating stations to Everett, Seattle and Tacoma. Length 160 miles (257.4 km.). Number of insulators 17,350, 4550 of which were in service at 30,000 volts for two years previous

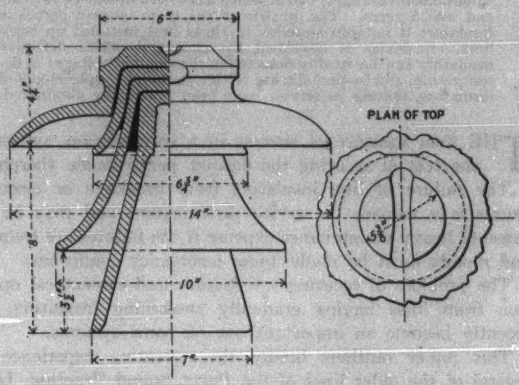


FIG. 1—INSULATOR FOR 60,000-VOLT CONSTRUCTION.

to the 55,000-volt service. Poles 35- to 55-ft. (10.6- to 16.7-m.), set on spans from 130 to 300 ft. (39.6 to 91.4 m.). Wires spaced seven and nine ft. (2.1 and 2.7 m.), and vary in size from No. 4 B. & S. copper to No. 4/0 B. & S. aluminum. Insulators screwed on iron pins.

OPERATING HISTORY

Line A. The insulators originally installed on Line A were among the first of their kind and voltage to be made, and the art of high-voltage porcelain manufacture was not well understood at that date. Their appearance indicates that the clay was worked quite dry and that probably the mixture contained

a much lower percentage of china clay than is now used. Many samples show a lack of homogeneity in the ware and irregularities of surface, and firing cracks are visible under the glaze. The shells were given a moderate test at the factory and shipped to Tacoma, where they were cemented together and the assembled insulators subjected to a dry test of 120,000 volts. Difficulties with the testing equipment made it necessary to put a portion of the insulators on the line without test. There were failures from time to time during the test, but as it was considered unusually severe, trouble was not anticipated.

Electrical failures began to occur within a short time after installation, especially during line surges and in wet weather, and have continued from time to time to date. The larger shells crack radially and leakage over the smaller shells burns off crossarms. These cracks stand open perceptibly, indicating that there were shrinkage strains in the ware.

It has been necessary gradually to replace these insulators, until at this date 83 per cent of the original installation has been replaced.

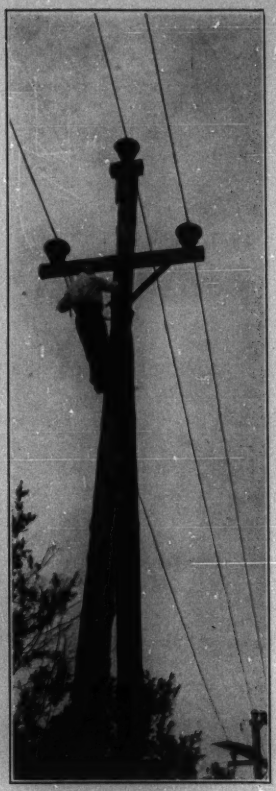
Line B. The insulators on this line were purchased and installed under the same conditions as Line A, but were made at a different factory. The appearance of these insulators indicates a much better grade of porcelain with a smoother surface, but some samples of them do not compare with the ware turned out of the factories today. Such of them as were tested showed a very small percentage of failures. For the first five years of operation, very little trouble was experienced with these insulators, but later on they began breaking down occasionally and recently they have given a good deal of trouble, failing several at a time during an arcing ground at another point on the system. A large number of these insulators were put on Line A to replace failures of the original insulators thereon, so that the total installation of the ware purchased for Line B is about 8200 insulators. Of these, the failures to date have totaled about 4 per cent, nearly half of which have been in the last year. These insulators do not usually have a large radial crack, but a small crack starts on the head or in the side groove and runs around on the top of the insulator. It seems that these cracks enlarge until a leakage current starts through the top two or three shells and discharges over the surface of the lower shell. The tendency of a brush discharge to pass in the positive direction more than the negative, has

a rectifying effect on the leakage current. This results in a partly unidirectional current from the bottom shell to the pin, and signs of electrolytic corrosion of the pin head in the cement have frequently been found. Once started, this will soon crack the entire insulator, as the high tensile stress put on the porcelain by this internal expansion will lower its dielectric strength. In many cases insulators have been found which were leaking noisily, and when the line was killed and an examination made, the insulator was found intact, although a number of cracks were visible. As soon as the tie wire was removed, however, the entire insulator fell apart.

Line C. The insulators on this line were made at several different factories and are of as fine a grade of porcelain as can be obtained today. A representative of the company at the factory tested each shell separately, and the assembled insulator, to 120,000 volts for five minutes. Every insulator was given this test and examined for physical defects, and stamped by the inspector if accepted. To date there have been only three failures, and it is possible that these were partially broken in some other way before failure.

A large number of insulators have been installed on pole lines and steel tower lines built within the last few years on this system, which were tested as in Line C and screwed on iron pins, and there have been no failures. About 120 strain insulators, each consisting of three 10-in. (25.4-cm.) diameter link type disks with no cemented parts, have been in service at strain points for three years without trouble.

The expense of replacing outright all the Line B insulators was prohibitive, and they formerly were replaced one by one when they got to the point where the leakage currents could be heard from the ground. This was not entirely satisfactory, however, as they were at an advanced stage of the deterioration before this condition was reached, and frequently failed, causing an arcing ground that punctured other insulators, and a heavy charge against maintenance resulted on account of the emergency nature of the repair work. The first method tried was by using a megger, but no satisfactory results could be obtained unless the testing wire was over the leaking crack and this crack extended clear through to the pin. Each insulator had to be untied and the testing work was very expensive and laborious. After considerable experimenting a device was perfected to locate these insulators at an early stage of the



[CRAWFORD]

FIG. 2—SHOWING METHOD OF USING DEFECTIVE-INSULATOR DETECTING SET

Hand pick consists of insulated tube with sharp pointed steel terminal on one end which is thrust into the pole or crossarm. A sharp steel pin forms the other terminal, which is driven into the ground or pole under the cross arm. A fuse and short-circuiting jack with plug on the receiver set may be inserted in the circuit if there is any probability of a considerable voltage to ground.

depreciating process, so that the work of replacing them could be done economically and before they broke down and damaged other insulators and interrupted service. This device is shown in Fig. 2 and consists of a pair of 2000-ohm wireless telegraph receivers, fitted up for the convenience and safety of the inspector in testing. The hand pick is driven into the pole about seven feet from the ground, and the sharpened pin driven into the ground several feet away. The receiver set is connected between these two, and if all insulators are sound there is a clear audible hum of the same tone as the telephone line, due to the shunting of a part of the capacity current of the insulators on the pole top. If, however, one of them is leaking, a scratching noise is superimposed on the hum, which comes and goes as the neutral shifts to and from the wire on the defective insulator. The inspector then proceeds up the pole and tests between each insulator pin and the center of the crossarm, and thus locates the defective one. This device can be used in a similar manner on steel tower lines. Insulators can be found in this way which have only a very small crack started and which will not puncture on the test below 100,000 volts. Insulators with a crack clear around the head were taken off and tested, puncturing at from 60,000 to 65,000 volts, but no sound was audible from them while on the line without the use of the detecting set. One or two lower petticoats were usually found intact, the leakage current passing over their surface during the test until the puncture point was reached.

Field books are kept with the record of the last test, and data on each insulator on every pole in Lines A and B. With practise the inspector can single out defective insulators which are at an early stage of the depreciating process. These tests can be made while the lines are in service, at very slight additional cost to the routine patrolling. Several hundred insulators can then be replaced at a convenient time and the work organized so as to be done economically. By keeping at this work at regular intervals, failures in service can be practically eliminated.

It seems probable from the history of operation that the porcelain on Lines A and B was of lower dielectric strength originally than that on Line C, and that many of these insulators were therefore under an electric stress which was a large percentage of their ultimate strength. Under these conditions

the poorer insulators soon failed, and the better ones gradually weakened, to fail later. The best insulators, however, as on Line C, are being operated at a potential which is a small percentage of their ultimate strength and are showing no signs whatever of weakening or fatigue, although they have only been in service five years. The Line A and Line B insulators began to weaken in less time than this, and it seems that if any process of fatigue were under way, some signs of it would surely be in evidence among 17,350 insulators after five years' service. Although the evidence is not conclusive, it seems probable to the writer that electrical fatigue of porcelain only occurs where the ware is operated under electrical or mechanical or combined stresses which are too close to its ultimate strength Insulators should be designed and individually tested to withstand at least 2½ times line voltage; and care should be taken that at high potentials, where unit insulators are in series, line voltage is taken as the actual portion of the total voltage which comes on each particular insulator in the string. Where the gradient is not uniform and potential is concentrated more on some units than on others, these units should be designed accordingly and tested as above.

The use of cemented-in metal parts should be avoided in connection with porcelain insulators, thus eliminating any possible trouble due to electrolytic corrosion if leakage currents occur, or due to expansion and contraction strains of the different substances. The use of screwed-on pin-type insulators decreases the cost of replacing, and while not quite as suitable for heavy side strains, the use of strain insulators is better practise for such points.

DISCUSSION ON "ECONOMY IN THE OPERATION OF 55,000-VOLT INSULATORS" (CRAWFORD), SPOKANE, WASH., SEPTEMBER 11, 1914.

J. Harisberger: What brought about the development of testing insulators as mentioned in the paper, was a severe storm in the Puget Sound district last winter, causing a number of breaks in our transmission line where it goes through heavily timbered country, these breaks causing arcing grounds and breaking down insulators all over the system. We had been very proud of our record of uninterrupted service, and this trouble set me to thinking about aging of porcelain that has been so much discussed recently. I have been unwilling to admit to myself that there is such a thing as the aging of porcelain, and I do not believe it now. Last spring I made a trip down the Coast to visit operating companies that have been operating lines of 50,000 volts or over for some time, to get what information I could as to their experience. I visited eight companies and found but one man who was positive that porcelain deteriorated and gradually lost its dielectric strength. I found that the experiences of most of the companies visited were quite similar to our own. The porcelain of some of the insulators in service five to six years, on close examination, showed a mottled surface similar to that of Dedham china ware. On breaking the insulator, discoloration of the cracks to a depth of one-quarter of an inch was occasionally found. There is no doubt that this condition cuts down the insulating quality of the porcelain and these insulators should be weeded out before they are broken down by some disturbance on the system. During my absence, Mr. Crawford developed the method as outlined in this paper for locating such insulators. I believe that everyone having had experience in the operating of high-voltage transmission lines will agree with me that high-frequency disturbances such as are caused by arcing grounds, etc., are most to be dreaded. While in California, I spent half a day with Professor Ryan, of Stanford University, who showed me a practical demonstration as to what high-frequency currents will do. An insulator that would show practically no distress at 150,000 volts at 60 cycles, would be punctured in a few seconds when subjected to over 100,000 cycles and not over 25,000 volts.

It is quite noticeable on our system that the majority of failures are insulators cemented to iron pins. Over seven years ago I objected to cementing insulators to pins and designed a pin with a flexible top for screwing on 60,000-volt insulators. I was much criticised and was told that I would get into trouble on account of the metal expanding and breaking the insulator. We have some 20,000 insulators in service of this type of construction, and I have yet to hear of a failure on account of this type of pin.

M. H. Gerry, Jr.: The design of high-tension line insulators is now pretty well understood, but, of course, it is still a question of effective material and proper distribution. The most important of all is the distribution of electrical stress. This has been discussed many times in the Institute PROCEEDINGS.

V. H. Greisser: The principal thing in this paper of interest to me is the fact that the telephones can be used for delicate practical tests, and we are very fortunate indeed to be able to secure some such instrument that is sensitive enough to test insulators. Practically the only instrument of any use on high-tension work previous to this, has been the oscillograph, and that has not been sensitive enough to be very useful in testing porcelain insulators.

A. A. Miller: I take it for granted that Mr. Greisser's last remark that the oscillograph does not afford the proper means of testing insulators referred to the work which Dr. Ryan has been performing in California, where he has used very high frequencies, away beyond the natural periodicity of the oscillograph, and found that it was very easy to puncture porcelain insulators by using such frequencies. He has a laboratory in which he very effectively demonstrates the ease with which porcelain is punctured by means of these very high frequencies, boring holes right through an insulator. Professor Ryan's investigations I think will throw a great deal of light on that.

H. R. Noack: There has been a great deal of discussion upon the subject of aging of porcelain. I think there is some misconception of the meaning of the term "aging." As I understand it, aging applies particularly to a molecular change in the porcelain itself. Porcelain is a very inert matter and, so far as any studies which I have been able to make on the subject are concerned, there has never been noticed any molecular change within the porcelain itself. The effects commonly considered as aging, I am satisfied, have nothing to do with molecular changes, but are generally due to external influences. For example: porcelain insulators as used today are generally in combination with other materials, such as cement and steel or iron, and some of the changes noted under operating conditions undoubtedly are due more to the influences of a combination of these different materials with different characteristics than to any inherent change in the porcelain itself. Again, there is no known standard, to my knowledge, as to what constitutes perfect or ideal porcelain; different manufacturers have different standards in mixing, firing and in manufacturing, generally, so that there is no one standard which has yet been established as to what constitutes ideal porcelain. Many of the troubles which have been noticed may, in my opinion, be ascribed to improper firing of the porcelain, assuming, of course, that in the first instance the mixture was suitable to make perfect porcelain if handled properly in the subsequent manufacturing operations. It seems to me that, eventually, engineers

will have to determine upon some standard for measuring perfect porcelain. An under-fired piece of porcelain is, to a certain degree, porous. The porcelain is almost invariably covered by a glaze, which is a glassy structure and protects the body of the porcelain from external influences, such as moisture and gases, but under operating conditions the glaze may be eventually injured, and even though it is not injured, there are some portions of the porcelain which are not covered by the glaze, due to manufacturing necessities, so that gradually there may be absorption of moisture, which, when subjected to heating influences due to electric currents, may cause expansion to such a degree as to gradually develop minute cracks, and these, though microscopic at first, will eventually grow in intensity, and finally allow the porcelain to puncture. On the other hand, the porcelain is sometimes over-fired, in which case it takes on a glassy structure and is not capable of resisting the influences of alternate expansion and contraction to the same degree as perfect porcelain.

The question of "aging" is one of great importance and, as I said in the beginning of my remarks, I do not believe that it has been demonstrated that any such phenomenon exists, but that the difficulties arising from so-called "aging" are due to external influences.

T. R. Cornick: I was with the Mexican Light & Power Company when its line was first put into operation. We had approximately 500 miles of 60,000-volt circuit and later 40 or 50 miles of 20,000-volt circuit. I was there for approximately five years after these lines went into operation and I do not think that I ever discovered any "aging." We did have a lot of trouble due to electrical disturbances and I should say approximately twenty punctures. Those punctures took place, however, when these electrical disturbances were on; therefore we did not call them the "aging" of the insulator. That line after being in operation at 60,000 volts for several years was increased to 80,000. The insulators of course were changed. To start with we used the Rio type, 14 1/2 in., which was changed to, I think, 18 in. when they went to 80,000 volts. Since they went to 80,000 volts they have had no appreciable increase of trouble. Our troubles all took place before we put on the ground-wire. After we put on the ground-wire our troubles decreased, from, you might say, every day of the rainy season (during six months of the year) to approximately three cases of trouble during the rainy season. We, therefore, took it that the trouble was purely and simply the lightning and not trouble with the insulators. Therefore, I think Mr. Noack is right in his discussion in that it isn't a case of "aging" of the insulators but is doubtless a case of poor mixing, or poor manufacture.

P. M. Lincoln: I ask Mr. Cornick if the ground wire was overhead?

T. R. Cornick: Yes, overhead ground wire.

L. T. Merwin: I can't offer anything from experience here in Washington, because the line of the company with which I am connected has been in operation only 17 months. I might say, however, the insulators that are now being put on the market are certainly remarkable for the factor of safety that is offered. I speak now from the experience of an instance on our line shortly after it was put into operation. It was on June 17th of last year, when we had a turbine runaway in our plant. After we had patched things up, and got the line in operating condition again, or rather got the plant in operating condition again, we tried to repeat the runaway under hand control, and one of the results that we obtained by interpolation and extension of the graphic lines on our charts showed that we must have had, during that runaway, an impressed voltage on the line of something between 150,000 and 200,000 volts. The line is of wooden-pole construction with steel-core aluminum conductors and pin type insulators, with four strain units in a dead end. The pin type insulators had cemented lead thimbles in the top of the insulators, the lead thimbles receiving a ¾-in. steel pin. Now, since that runaway and the impressing of that extremely high voltage on our line we have not had a single breakdown, neither did we have a single breakdown up to that time. The line was put in operation on the 25th of April, 1913, and on June 17th the runaway occurred with this high impressed voltage. It is now approximately fifteen months, and we have yet to experience our first insulator failure.

I might also add that on another occasion our insulators withstood a severe arcing ground for 1¾ hours before the faulty section could be cut out by open air switching. This occurred quite recently, with no bad results.

Incidentally, our lines are delta-star connected with ungrounded neutral, and I was able to carry load through this very severe arc. Now it is, I should say, a remarkable thing that insulators have such a large factor of safety as to stand a voltage of two to three times the working voltage. The farmers along our line described the spectacle as being awe-inspiring. Of course any high arc is awe-inspiring to the layman; but from reports our line must have been lit up with corona from one end to the other and apparently looked like a solid streak of fire from the White Salmon river clear through to Camas. So if there is any aging in insulators it certainly has not appeared yet in the seventeen months of operation, and there certainly were no immediate bad results.

L. J. Corbett: There is one point that I would bring up here which has not been touched upon as yet, and that is the matter of glass insulators and their possibilities. We have heard thus far only regarding the changes in the porcelain insulators. The porcelain manufacturers have been busy for some time and have been doing very effective work, and they appear to have a very reliable product at the present time. It seems

to me that glass, with its superior insulating qualities, should be worked upon a little more by the glass manufacturers and it may be possible that a more effective insulator, an insulator more constant in its qualities, could be developed. The objection I believe is the uncertainty of glass in its mechanical strength. The difficulty about the porcelain is the uncertainty in its electrical strength, and I would like to see in the future more development in that line if there are actual possibilities.

Ralph W. Pope: I have been thinking of glass during this discussion. Mr. Field, who was one of the early electrical engineers in California, stated that the possibilities of glass for long-distance transmission insulation had been overlooked; and I may say, in reply to Mr. Corbett, that the manufacturers have gone into this question very thoroughly, and some of the data as regards tests will be found in the TRANSACTIONS, 1912, XXXI, p. 2195. If there is any doubt as to the relative qualities of porcelain and glass it would be wise to put them in operation at the same time and study the results simultaneously so that if there is a possibility of the glass insulator being better it could be ascertained in that way. In the discussion which took place at the Cooperstown convention on insulators the question of mixing of porcelain came up for consideration, and it appears to have been maintained that it wasn't the business of the electrical engineer to go into the mixing of porcelain, but that that was the work of the ceramic engineer. There is no doubt but that the manufacturers of porcelain insulators are investigating this; but, as it appears to me, it is a rather difficult matter, and the committee found it so, to arrive at a standard of perfect porcelain. The mechanical stress is a very important feature, and I think that is particularly what the manufacturers had in view in the construction of glass insulators. Those can be obtained now, I believe, in almost any form, and I think it would be worth while for engineers to test out their possibilities.

M. H. Gerry, Jr.: There is considerable misunderstanding on the subject of glass insulators. Glass is weaker mechanically than porcelain, and is also subject to internal strains, which may cause cracking when exposed to varying temperatures. The internal strains can be obviated to a considerable extent by proper design and can be materially reduced by careful annealing during manufacture. Glass insulators in many instances will give most excellent results; they are always cheaper and often better than porcelain insulators. I have had personal experience with over 200,000 glass insulators under operating conditions at voltages from 25,000 to 70,000, and I have never known an electrical failure traceable directly to the material. Where trouble has occurred, it has been due either to defective design, improper annealing or too great mechanical strain on the insulator. It would be impossible to make a statement of this kind for porcelain, as a great many electrical failures have been due to defective material.

A. A. Miller: I ask Mr. Gerry whether or not he considers the new form of insulators, in which there are disks placed in series to each other, contributes in any way to the elimination of these internal strains. In other words, the disks, it seems to me, would contribute to the elimination of these internal strains a great deal more than the petticoat insulators.

M. H. Gerry, Jr.: It is entirely a question of proper annealing of the glass during manufacture and the relative proportions of the different parts of the insulator.

E. Woodbury: I ask Mr. Harisberger if he can tell how they would apply this test of the telephone receiver in case of a tower line or a wooden structure having pins grounded.

He also mentioned that probably it was bad practise to have cemented pins in the insulators; in view of this, do they use insulators with cemented-in metal thimbles, or are the insulators screwed directly onto the pins?

He also mentioned link-type strain insulators. It is my understanding that that type is not now manufactured, and that all suspension type insulators, therefore, would have cement. In line with his remarks on insulator troubles, we have been in the habit of shutting down at convenient times our lines having pin-type insulators, and tapping the insulators with a stick to determine the cracked ones. On the coast where we had considerable trouble with burning off of poles and cross-arms on a 15,000-volt line, we have connected the iron pins together with a wire and have stopped absolutely all the burning of poles.

J. Harisberger: I have not had any experience with glass insulators for high-voltage lines, but if anyone is qualified to speak on that subject, Mr. Gerry is.

We have had no occasion for locating faulty insulators on tower lines, as we have only some 12 miles of tower line and the insulators have only been in service a little over two years and have given absolutely no trouble.

In answer to Mr. Woodbury's question, I will say that insulators cemented to iron pins have a threaded $1\frac{3}{8}$-in. pin hole. Whenever an insulator is broken, we do not change the pin, but place a threaded sleeve of soft metal over the top of pin and screw on a new insulator. This sleeve was designed for this purpose and costs about two cents.

Presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Spokane, Wash., September 11, 1914.

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REPORT
by the
JOINT COMMITTEE ON INDUCTIVE INTERFERENCE
to the
RAILROAD COMMISSION OF THE STATE OF CALIFORNIA

Scope

THIS report presents briefly an account of the formation of this Committee, its activities and results accomplished to date, and recommendations for such rulings by the Railroad Commission of the State of California as the Committee believes are justified at this time; together with a technical discussion in explanation of the results and recommendations.

Historical

The formation of the Joint Committee on Inductive Interference was the outgrowth of certain differences involving power, communication and railroad interests which were brought to the attention of the Railroad Commission of California. As an alternative to contesting the issue at that time it was agreed by the power and communication companies, with the approval of the Commission, that a joint investigation should be made to obtain certain information essential to a proper solution of the difficulties. The Commission desired that the matter be thoroughly investigated before passing upon the general principles involved in these difficulties. To this end a general conference was called to select representatives to form a "Joint Committee" empowered to conduct tests, experiments and investigations, the results of which would serve as a basis of recommendations for rules and regulations, to be issued by the

Commission, tending to minimize inductive interference and physical hazard arising from parallelism of different classes of circuits. This conference was held December 16, 1912. As a result, the Joint Committee on Inductive Interference, representing the Railroad Commission and railroad, power, and communication interests of the State, was organized and authorized by the Railroad Commission of California to conduct the desired investigation.

The organization and personnel of the Joint Committee on Inductive Interference were approved by the Railroad Commission on January 6, 1913, and the Committee thereupon proceeded with the necessary tests and investigations.

For the more efficient conduct of its work the Joint Committee was divided into several smaller sub-committees, each assigned to, and responsible for, certain branches of the investigation. The present organization of the Joint Committee is given on a chart presented as Appendix VI.

Early in its work the Joint Committee established a field engineering staff reporting to the Sub-committee on Tests, to conduct the necessary tests and investigations. This field staff was composed of engineers in the employ of The Pacific Telephone and Telegraph Company and the American Telephone and Telegraph Company and was later augmented by the addition of two engineers and a stenographer engaged by the Joint Committee.

Previous to the formation of this Committee in December 1912, The Pacific Telephone and Telegraph Company had started an investigation of inductive interference between the lines of the Coast Counties Gas and Electric Company and the lines of the telephone company in the neighborhood of Morganhill in Santa Clara County. This investigation was completed by the Joint Committee and its results have been considered in connection with other work carried out by the Joint Committee.

In January, 1913, the Joint Committee established its field staff at Salinas, to investigate parallels on the lines of the Sierra and San Francisco Power Company north of Salinas and on the lines of the Coast Valleys Gas and Electric Company south of Salinas, both of these power lines being parallel with lines of The Pacific Telephone and Telegraph Company, the Western Union Telegraph Company and the Southern Pacific Company's signaling system. The investigation at Salinas continued from January 1913 until July 1913.

The specific work undertaken at Salinas was: a determination of the magnitude and characteristics of the induction produced in the communication circuits, the factors in the power circuits causing this induction, the quantitative relationship of cause and effect, and a comparison of the effects on the parallels north of Salinas with the neutral of the power circuit alternatively grounded beyond one end of the parallel and beyond both ends of the parallel.

In July 1913 the field headquarters were moved to Santa Cruz. At this point the Committee desired to test the relative merits of various schemes of transposition for both power and telephone circuits, and to complete the investigation begun at Morganhill on the system of the Coast Counties Gas and Electric Company, which system is of a different character from that studied at Salinas. A mathematical study of transpositions in general, and particularly of those for the parallel between Santa Cruz and Watsonville, has been completed. The experimental study of these schemes of transpositions has not as yet been completed.

Owing to the peculiar nature of the experimental work and the refinements required, suitable apparatus was not easily obtainable and in many instances it was necessary to design and develop special apparatus for certain of the tests. A considerable amount of time has necessarily been spent at all points of the tests in choosing, from the almost innumerable things which could be investigated with profit, those of greatest value which could be carried out with the means at hand.

In the course of its investigations the Committee has prepared a series of fifty technical reports which present and discuss in detail the various features of the work, the methods and apparatus employed and the results accomplished. These reports, which are on file at the Committee headquarters in the offices of the Railroad Commission of California, are listed in Appendix V.

Results Accomplished

The following paragraphs summarize very briefly the principal results accomplished to date. These statements of results are accompanied by brief explanatory comment upon the conclusions reached. The reasons for and explanations of these conclusions are given in more detail in the appendices to which reference is made.

1. *Interference to telephone circuits under normal operating conditions of power circuits arises almost wholly from the harmonic voltages and currents of the power systems.* (*See Appendix I*).

This is due chiefly to the fact that the frequencies of the harmonics generally present in the voltages and currents of power systems cover a considerable portion of the range of the voice frequencies, particularly those frequencies at which telephone instruments and the human ear are of maximum sensibility. Extraneous currents of frequencies approaching the average voice frequency have a more injurious effect upon telephone conversation than currents of lower frequencies.

2. *The effect of induction of the fundamental frequency on telephone circuits is comparatively unimportant unless it is of magnitude sufficient to constitute a physical hazard.* (*See Appendix I*).

This is due to the fact that the fundamental approaches the lower limit of audible frequencies, at which the telephone and the human ear are not efficiently responsive.

3. *Interference to telegraph and other signaling circuits is due principally to the fundamental and lower harmonics.* (*See Appendix I*).

Telegraph receiving instruments are relatively insensitive, as compared with the telephone, to the higher harmonics, but are sensitive to disturbances of lower frequencies, such as the fundamental and lower harmonics which more nearly approach the normal operating frequency of such circuits.

4. *The power circuit currents and voltages may be divided into two factors: balanced and residual, of which, for equal magnitudes, the latter in general produce the greater inductive interference.* (*See Appendix II*).

Residual currents and voltages act inductively in a similar manner to single-phase currents and voltages acting in a circuit composed of the line conductors in parallel with earth return, which is a condition favorable to very large induction. Moreover, such a circuit which includes the earth as one side cannot be transposed. Transpositions in the power circuit cannot reduce the inductive effect of residuals except as they reduce the magnitudes of the residuals themselves, which they do in some cases. The inductive interference arising from such currents and voltages can be reduced only in the case of metallic circuits such as telephone circuits, by transposing these circuits. It is therefore important that the telephone circuits be trans-

posed at frequent intervals throughout parallels and carefully balanced throughout their entire length and that the residual currents and voltages be kept sufficiently small to give negligible induction in telephone circuits so arranged.

5. *Inductive interference to communication circuits, arising from the balanced voltages and currents, can in a large measure be prevented by means of an adequate system of transpositions applied to both power and communication circuits (assuming the latter are metallic) and located with due regard to each other.*

This is accomplished partly by creating mutually neutralizing inductive effects in neighboring lengths of each side of the communication circuit or circuits by transposing the power circuit, and partly by equalizing the inductive effects on the two sides of the communication circuit or circuits by exposing each side equally to the influence of the power circuit by transposing the communication circuit.

6. *Abnormal conditions and at times switching operations produce transient disturbances of a very severe character.*

This is due to the fact that abnormal conditions almost invariably give rise to residuals of large magnitude, often including high harmonics. Abnormal occurrences incident to electrical power transmission do not give warning of their occurrence, and since they cannot be produced artificially on transmission systems without subjecting the apparatus to great risk or danger, it has been deemed unwise to attempt any experimental tests of these effects. This conclusion is therefore drawn from general experience and data of actual occurrences collected by the Committee.

Rules Recommended by the Committee

The following are the rules which the Committee, as the result of its study to date, recommends be issued at this time to govern the future construction and operation of power and communication circuits which are or are proposed to be so located as to create a parallel as hereinafter defined.

Outline of Rules

Definitions.

a. Power Circuit
b. Communication Circuit
c. Telephone Circuit
d. Line.
e. Parallel or Parallelism

f. Residual Current
g. Residual Voltage
h. Transposition.

I. Avoidance of Parallelism

II. Conditions under which Parallelism will be Permitted.

a. Minimum Horizontal Separation
b. Balance of Power System
c. Limitation of Residual Currents and Voltages
d. Transpositions Inside Limits of Parallel
e. Transpositions Outside Limits of Parallel
f. Uniformity of Parallel
g. Transformer Connections
h. Switch Equipment
i. Switching
j. Use of Air Switches
k. Abnormal Conditions
l. Devices for Indicating Abnormal Conditions on Systems Isolated from Ground.
m. Procedure under Abnormal Conditions
n. Ammeters in Neutral Ground Connections
o. Charging Electrolytic Lightning Arresters
p. Wave Form of Rotating Machines
q. Exciting Current of Transformers.

III. Provisions Applying to Existing Parallels

IV. Waiver of Conditions by Communication Company

V. Parallelism with Alternating-Current Railways.

Definitions

The following definitions are given of certain technical terms employed herein:

a. *Power Circuit.* The term "power circuit" includes any overhead constant-potential alternating-current power transmission or distribution circuit or electrically connected network which has a voltage of five thousand volts or more between any two conductors or of three thousand volts or more between any conductor and ground.

b. *Communication Circuit.* The term "communication circuit" includes any overhead, open wire telephone, telegraph, or signaling circuit which is used in the service of the public.

c. *Telephone Circuit.* The term "telephone circuit" includes any inter-exchange metallic telephone circuit, and therefore excludes subscriber's circuits. This term also includes any metallic telephone circuit operated by any railroad or other company for dispatching purposes or for public use between separate communities.

d. *Line.* The term "line" means any circuit or aggregation of circuits carried on poles or towers.

e. *Parallel or Parallelism.* The terms "parallel" or "parallelism" refer to cases where a power line and a communication line follow substantially the same course, or are otherwise in proximity for a sufficient distance, so that the power circuit is liable to create inductive interference in the communication circuits.

f. *Residual Current.* The term "residual current" denotes the vector sum of the currents in the several conductors of a power circuit.

g. *Residual Voltage.* The term "residual voltage" denotes the vector sum of the voltages to ground of the several conductors of a power circuit.

h. *Transposition.* The term "transposition" denotes the interchange of position of the several conductors of a circuit.

I. Avoidance of Parallelism

Every reasonable effort shall be made to avoid new parallelism. The party proposing to build a new communication or power line, which will create a parallel, or generally to reconstruct an existing line involved in a parallel shall give due notice (at least thirty days wherever possible) of its intention to the other party, including detailed information as to the location and character of the proposed line. If a plan can be devised and agreed upon by the two parties for maintaining an adequate separation between the two classes of lines so as to avoid interference, this shall be done. In case it is impracticable to secure adequate separation between a power line and a communication line, parallelism will be permitted subject to the conditions set forth in II.

II. Conditions under which Parallelism will be Permitted

a. *Minimum Horizontal Separation.* The minimum horizontal separation between the power line and communication line shall be equal to the height of the taller line. The only exceptions to this provision are angle crossings and other unavoidable cases of close proximity, and in all such cases the power line shall be kept above the communication line and constructed in conformity with the National Electric Light Association's specifications for overhead crossings or other approved equivalent which may be agreed to by both companies.

b. *Balance of Power System.* The power company shall exercise due diligence to keep the currents in, and the voltages to ground of, the conductors of any power circuit involved in a parallel, as closely balanced as practicable. In all cases where telephone circuits are involved, special consideration shall be given to the prevention or elimination of harmonics in the residual current and in the residual voltage.

c. *Limitation of Residual Currents and Voltages.* Pending additional rules on specific means other than those given herein, the parties concerned shall endeavor to agree upon the means to be employed for the prevention or limitation of residual currents and voltages, and in the event of disagreement the

matter shall be referred to the Railroad Commission of the State of California.

d. *Transpositions Inside Limits of Parallel.* An adequate system of transpositions shall be installed in the power circuit (or circuits), and in the communication circuit (or circuits) provided the latter is metallic. When both circuits are transposed the transpositions in both the communication and power circuits shall be located with due regard to each other.

Every reasonable effort shall be made by both parties concerned to fix the limits of the parallel and the location of crossings, branch lines, and connected apparatus so as to facilitate the application of an effective transposition scheme.

In the case of a parallel between a power line and a telephone line the company owning or operating the telephone line involved shall have the right to specify the number, type (in respect to electrical characteristics) and location of the transpositions in the power circuit, subject to the following limitations:

1. For power circuits of 50,000 volts or over, the average distance between successive transpositions shall not be required to be less than one mile and the minimum distance between any two successive transpositions shall not be required to be less than two-thirds of a mile.
2. For power circuits of less than 50,000 volts the distance between successive transpositions shall not be required to be less than one-sixth mile.

The transposition system of the telephone circuits shall be modified where necessary in order that the power and telephone circuits shall be, as nearly as practicable, mutually non-inductive.

For short parallels less than six miles in length (or short sections of longer parallels which have to be treated independently because of abrupt change in conditions) with power circuits of 50,000 volts or over, where it is impracticable to obtain an adequate balance by the location of transpositions in accordance with the limit specified above, the company owning or operating the telephone line involved shall have the right to specify the number, type and location of transpositions provided the distance specified between successive transpositions is not less than one-half mile.

When necessary (due to variations in lengths of telephone transposition sections) in order to secure an adequate balance, a reduction of 10 per cent in the limiting distances between successive power circuit transpositions as given above, shall be allowed.

In the case of a parallel between a power line and a tele-

graph line or other grounded communication circuit, the location of the transpositions in the power line shall be with due regard to the limits of the parallel in order to form as nearly as practicable a balanced system. The location and type of such transpositions shall be as specified by the communication company, subject to the condition that the transpositions in the power circuit may not be required to be less than one mile apart.

In no case shall the power company be required to relocate poles or towers for the transpositions.

The parties concerned in any proposed parallel shall endeavor to agree upon a transposition scheme for such parallel in accordance with the above. In the event of a disagreement, the matter shall be referred to the Railroad Commission of the State of California.

e. *Transpositions Outside Limits of Parallel.* In addition to transpositions within the limits of a parallel, as provided in "d" hereof, each new power circuit isolated from ground (or extension of such existing circuit) which is constructed subsequent to the date when these rules become effective, shall be transposed throughout its entire length in such manner as to balance the electrostatic capacities to earth of its several conductors, so as to avoid inequalities among the voltages to earth of the several conductors, which would create inductive interference. Such transpositions shall not be more than eight miles apart, provided however, that circuits less than three miles in length are not required to be transposed until they are extended to a greater length; except that extensions or spurs from existing lines, the electrostatic capacities to earth of whose conductors are balanced, shall be so constructed as not to change materially the balance of the existing lines to which they are connected.

f. *Uniformity of Parallel.* To facilitate the application of effective transpositions, both parties shall endeavor to maintain uniform separation, uniform arrangement of conductors and uniform relative location of the two classes of circuits within the limits of a parallel. However, when it is feasible to secure a substantial increase of separation between the two lines for a considerable portion of a parallel, this shall be done, as such an increase of separation is of more benefit than uniformity.

g. *Transformer Connections.* (1) On any power circuit involved in a parallel, no grounded single-phase, or grounded open-star transformer connections shall be employed.

NOTE: This does not apply to railroads operating alternating-current trolleys with ground return, which are covered by V.

(2) On a power circuit involved in a parallel, no star-connected transformers or auto-transformers with grounded neutral shall be employed, unless delta-connected secondary or tertiary windings or other equivalent means are used of suppressing the third harmonic components of the residual voltages and currents introduced by the transformers.

(3) Where single-phase loads are connected to a polyphase power circuit involved in a parallel, the power company shall endeavor to arrange successive connections of this type so as to equalize the loads upon the several phases.

(4) On a three-phase circuit involved in a parallel, the power company shall use, wherever practicable, a closed-delta connection in preference to an open-delta connection, and where the latter is employed an effort shall be made to distribute such connections equally upon the several phases.

h. *Switch Equipment.* A power circuit involved in a parallel shall be equipped, between the source of supply and the parallel, with oil switches, all poles of which shall be mechanically interconnected for simultaneous action. With the exception of stations where an operator is constantly on duty, these switches shall be rendered automatic for short-circuits, grounds, and abnormal neutral currents.

i. *Switching.* All switching on all parts of a system connected to a circuit involved in a parallel, which causes harmful transient disturbances in communication circuits, shall be done by means of oil switches, all poles of which are mechanically interconnected for simultaneous operation.

j. *Use of Air Switches.* The use of air switches, on a power circuit involved in a parallel, is prohibited except for purposes of isolating sections of dead line, or for disconnecting transformers under no load. This applies to the entire power system, any circuit of which is involved in a parallel, unless such switching is so remote as not to cause harmful transient disturbances in the communication circuits.

k. *Abnormal Condition.* A power circuit involved in a parallel shall not be operated at any time with an open, grounded or short-circuited line wire or wires or transformer winding.

l. *Devices for Indicating Abnormal Conditions on Systems Isolated from Ground.* If a power circuit involved in a parallel is electrically isolated from ground, reliable indicating devices

shall be installed at its source of supply to inform the operator immediately of abnormal conditions, such as grounds and wherever possible, open circuits, which have not operated automatic switches. Upon indication of trouble by such devices, the operator shall immediately open the oil switches and proceed in the manner outlined in "m".

m. *Procedure under Abnormal Conditions.* In case of the opening of an oil switch due to an abnormal condition in a power circuit involved in a parallel, or any circuit supplying or supplied by the same, such switch may be closed once; if opened a second time due to the continuance of the fault or abnormal condition, said switch shall not be closed again until the line has been sectionalized. The fault may then be located by energizing sections of line, provided that further sectionalization of the line be done in such sequence as to cause the minimum disturbance to parallel communication circuits, and provided further that where practicable the faulty section of line shall be energized but once in this process of sectionalization, where the fault exists within or beyond the parallel, until such fault is remedied.

n. *Ammeters in Neutral Ground Connections.* Wherever a neutral ground connection is employed on a circuit involved in a parallel, an ammeter, suitable for measuring as accurately as practicable the current in the neutral under normal operating conditions, shall be installed in all neutral connections at the main generating and substations on the power system electrically connected to the circuit involved in the parallel. The power company shall maintain a record of hourly measurements of the neutral current at all such points.

o. *Charging Electrolytic Lightning Arresters.* Where a power system is equipped with electrolytic lightning arresters so charged as to cause inductive interference in communication circuits the method of charging the arresters shall be modified to eliminate the disturbances as far as possible. The charging of such lightning arresters shall be done at such time as to give the minimum liability of interference with communication circuit operation, preferably between the hours of 2 A.M. and 4 A.M.

p. *Wave Form of Rotating Machines.* The power company shall make every effort to obtain generators and synchronous motors for use on all parts of the system, giving, as nearly as reasonably possible, pure sine waves of voltage at fundamental frequency. In no case shall the deviation from a pure sine

wave exceed the limit set forth in the Standardization Rules of the American Institute of Electrical Engineers.

q. *Exciting Current of Transformers.* In order that the wave shapes of voltage and current may be distorted as little as practicable by transformers, the main line transformers employed on circuits involved in a parallel and on future extensions of such circuits shall have an exciting current as low as is consistent with good practise, and in no case shall the exciting current at rated voltage exceed ten per cent of the full load current. Such transformers shall not be operated at more than ten per cent above their rated voltage.

III. Provisions Applying to Existing Parallels

The following sections of II shall apply also to power circuits involved in existing parallels; b, i, j, k, l, m, n, o, p, and q. Also g-3 and g-4 shall apply to existing parallels to the extent that transformers added hereafter shall be connected as provided in said rules.

IV. Waiver of Conditions by Communication Company

At the option of the company operating the communication circuit or circuits any of the provisions of II and III may be waived.

V. Parallelism with Alternating-Current Railways

It is recognized that railroads operating alternating-current trolleys with ground return create serious inductive interference with parallel communication circuits. In the present state of the art, no means for completely overcoming inductive interference from such parallels is known, hence, they are to be avoided if possible and where unavoidable, the responsibilities arising therefrom must be settled by mutual agreement or in case of inability to agree the matter shall be referred to the Railroad Commission of the State of California.

Discussion of Rules

It will be noted from the definitions that the terms "power circuit" and "telephone circuit" are used in these rules in a special, restricted sense.

(I) The first and most obvious means of preventing inductive interference is to avoid the close association of power and communication circuits. Further, it is recognized that in no other way can complete freedom from interference be secured. While with the ever increasing network of electrical circuits of all

kinds, adequate separation to avoid interference is becoming increasingly difficult to maintain, the Committee feels that the importance of such separation justifies its being made the first premise in rules designed to prevent inductive interference.

Notice, sufficiently in advance, should be given the other party or parties concerned in any proposed parallel in order that thorough consideration may be given by both parties to possible means of avoiding the parallel, or, in case the parallel cannot be avoided, to the necessary remedial measures to be employed.

(II-a) The best insurance against physical hazard in cases of close proximity is to maintain a separation equal to the height of the taller line, thus avoiding the possibility of physical contact in case of failure. In the case of crossings and unavoidable cases of close proximity for short distances extra-strength construction is necessary as a precaution against failure.

(II-b-c) As has been pointed out under the heading "Results Accomplished", and more fully explained in Appendix II, residual voltages and currents are particularly troublesome factors in causing interference. Means to eliminate or reduce such residuals in power systems are highly important and while information at this time does not enable the Committee to formulate as explicit a rule as is desirable, yet the importance of the subject justifies its inclusion in the rules. The acquisition of further information on which to base a more explicit rule upon this subject is a most important problem, the experimental study of which is discussed in the following section of this report.

(II-d) Transpositions properly located in both power and communication circuits offer the most reliable and effective means for preventing interference from balanced voltages and currents of power circuits. While the inductive effects increase in severity for the higher voltage circuits, due in part to the increased separation of the line conductors, which renders more frequent transpositions desirable, the mechanical difficulties involved are so great as to over balance the other reasons and the rules, therefore, provide for less frequent transpositions in the higher voltage circuits than in the lower voltage circuits. A further reason for frequent transpositions in the lower voltage circuits is the necessity of a flexible system of transpositions applicable to short parallels which generally occur with such circuits.

(II-e) The provision requiring transpositions outside the

limits of a parallel on systems electrically isolated from ground is an explicit measure for carrying out the purpose of the more general provision given under II-b-c, "Balance of Power System" and "Limitation of Residual Voltages and Currents."

(II-f) Non-uniformity of separation and type of construction within the limts of a parallel are inequalities which cannot in many cases be taken into account in the design and layout of transposition schemes. Such inequalities tend to nullify the effectiveness of the transpositions; hence, it is desirable that they be avoided. A precautionary statement is included in the rule in order that the possibility of securing a wide separation for a considerable portion of a parallel may not be sacrificed for the sake of absolute uniformity throughout the entire length.

(II-g) Some types of transformer connections and methods of operation give rise to large residual voltages and currents and certain provisions of the rules are designed to prohibit or restrict the use of such connections and methods of operation. These rules may be considered as explicit provisions complying with the general provision in II-b-c, "Balance of Power System" and "Limitation of Residual Voltages and Currents". The sufficiency of these specific provisions as an insurance against harmful residual voltages and currents is subject to future determination.

The present information of the Committee does not warrant the definite recommendation of any one type of connection or method of operation as best from the standpoint of inductive interference. This is true as to the relative merits of the two general types of systems, the grounded neutral and the isolated system. The advantages and disadvantages of these general types and any modifications of these types are dependent upon their inherent characteristics in respect to residuals and the limitations and control of residuals under both normal and abnormal conditions. Both types are on an equality with respect to the interference caused by balanced voltages and currents.

(II-k) Continued operation under certain abnormal conditions is possible in some power systems. In particular, it is possible to operate a grounded star-connected system with one phase open, and it is possible to continue the operation of an isolated system when one phase becomes grounded accidentally. The former gives rise to a large residual current and the latter to

a large residual voltage, both of which are liable to render parallel communication circuits inoperative. For these reasons the rule prohibits such operation, which, aside from the consideration of inductive interference, does not constitute good practise in power system operation.

(II-h-1-n) To provide that operation under the abnormal conditions mentioned above may not continue without the knowledge of the power company, the rules specify that devices for indicating grounds shall be installed on isolated systems. With respect to grounded star-connected systems, the rules specify with certain exceptions the automatic opening of switches by abnormal neutral currents. In such systems ammeters are required in all main neutral ground connections. Such ammeters, read regularly, afford means of detecting abnormal neutral currents and are of value in showing the degree of balance of the system, as the neutral current is easily affected by unbalanced conditions.

(II-m) Accidental causes give rise to occasional abnormal conditions. These can only be guarded against by good construction and maintenance, and careful operation which, however, cannot prevent entirely such occurrences. When trouble develops on a power circuit involved in a parallel, it is always liable to cause serious interference to the communication circuits, if the exposure is severe. In the present state of the art, the method of fault location on power circuits is a process of repeated sectionalization and energization of the faulty line until the fault is located within certain limits. This process causes repeated interruptions with loss of time in the operation of the communication circuits, and in the case of telephone circuits is accompanied sometimes by injury to the operators. It should be explained that the loss of time is much greater than the duration of the disturbance, owing to the time required to restore the protective devices on the communication circuits to their normal condition. No method of locating faults on power circuits is known which meets the requirements of practise and yet avoids the disadvantages of the present method. The inductive disturbances due to fault location can be to a considerable degree ameliorated by disconnecting the faulty line from the rest of the system and energizing this line by a single generator at such excitation as may be necessary to overcome the insulation of the fault. Whenever practicable this method is employed by power companies; hence, it has not been thought necessary to cover it by a specific rule.

In view of these facts, the Committee is recommending the limitation of the present practice in this regard so as to avoid, as far as seems practicable, the repeated interruptions to communication circuit operation. It is highly desirable that some better method of fault location be developed, not only because of the attendant consequences of the present method on communication circuits, but also because of the abnormal strains to which the power apparatus is necessarily subjected.

(II-h-i-j) Normal switching operations on power circuits produce at times severe transient disturbances in parallel communication circuits. The commonly recognized fact that oil switches produce less severe transient disturbances in power circuits, affords the basis for the provisions in the rules dealing with switches and switching. The automatic features required are designed to prevent continued operation under abnormal conditions.

(II-o) Transient disturbances of severe nature to telephone circuits are sometimes caused by the charging of electrolytic lightning arresters. There are available methods of diminishing the transients due to this cause, and a general provision to the effect that such methods shall be employed when necessary, is included in this rule. It is further provided that the charging of the arresters should be done at times when the telephone circuits are least used.

(II-p-q) Fundamentally, interference to telephone circuits by power circuits in normal operation is largely due to the existence of harmonics in the currents and voltages. While the complete elimination of these harmonics seems impracticable, still beneficial results may be obtained by practical efforts in this direction and the Committee feels that the two general provisions as to the wave form of rotating machines and the exciting current of transformers are of great importance both from a practical standpoint and also as enunciating a general principle. The matter of generator wave form particularly is of importance for all types of systems. The provision with reference to the exciting current of transformers, while desirable in all cases, is particularly so on grounded star-connected systems.

(III) Certain of the measures in II, particularly those referring to power system operation, which are helpful in mitigating inductive interference, have been recommended to apply to existing parallels.

(IV) Since these rules are designed for the protection of communication circuits, it is proper that the companies operating such circuits be given the right to waive any measures of protection which they may in any particular case consider unnecessary.

(V) The Committee has undertaken no investigation of cases of parallelism with alternating-current railways, but as the seriousness of this class of exposure is recognized, it was thought desirable that it be referred to specifically.

Future Work

The further work necessary in order to secure the information essential as a basis of determining more explicit and effective rules than those herein recommended, is particularly concerned with the subjects of transpositions and residual voltages and currents. In order to cover these subjects in as effective and economical a manner as possible it is thought that the procedure should be along the following lines:

1. Experimental study of transpositions, which includes the determination of:

a—the practical effectiveness of transpositions in both power and communication circuits as a means of reducing induction arising from balanced voltages and currents; involving considerations of different coordinated transposition schemes, particularly with different lengths of power circuit "barrels."*

b—the practical effectiveness of transpositions in communication circuits as a means of reducing inductive interference arising from residual voltages and currents; involving considerations of different systems, particularly different lengths of balanced communication circuit transposition sections.

c—the influence of imperfect electrical balance of communication circuits in impairing the effectiveness of transpositions.

d—the practical effectiveness of transpositions in a power circuit isolated from ground as a means of balancing the electrostatic capacities to earth of the several conductors, and thereby reducing residual voltages and currents; involving considerations of the relative efficiency of different lengths of power circuit barrels.

2. Experimental study of the causes and effects of residuals, including:

a—a comparison of the different types of power system connection and apparatus in common use and their characteristics in respect to the production of residuals, particularly harmonic residuals.

b—means to be employed in limiting residual voltages and currents.

c—a determination of the minimum values of residual voltages and currents which will produce harmful inductive interference.

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*See Appendix III, page 1474.

It is thought that these two studies could progress simultaneously. The work indicated under (1) could best be done on an actual parallel selected to be as uniform and as free from secondary disturbances as possible. Some preliminary work has been done along these lines which indicates the best methods of procedure and this should facilitate the carrying out of the investigation.

The study mentioned under (2) consists in part of an investigation of the characteristics and magnitude of residual voltages and currents in typical power systems, both those with grounded neutrals and systems entirely isolated from ground. A part of the study of residuals is logically related to the study of transpositions and could be carried out in connection with the study outlined under (1) and at the same time and place.

In addition to the above the Committee has already arranged for the investigation of the two following subjects:

1—a determination of the detrimental effect of extraneous currents on a telephone circuit as a function of the frequency, including a determination of the maximum amount of extraneous current, of different frequencies and combinations of frequencies, which is allowable in a commercial telephone circuit.

2—a determination of the effects of extraneous current of different amounts and characteristics, in limiting the speed of telegraph operation.

This work is now in progress.

APPENDIX I

Harmonics

Any complex electrical wave of periodic structure may be resolved into component sine waves of suitable amplitudes and phase differences, having frequencies which are in integral relation to the fundamental frequency. The simple sine wave of lowest frequency is termed the fundamental, and those of higher frequency are termed harmonics of the fundamental wave. The fundamental may be considered the first harmonic. The analysis of a periodic wave into its constituent sine waves or harmonics is not merely a mathematical conception or process but is in accordance with the facts of electricity and acoustics.

In general, alternating-current systems, by virtue of their inherent characteristics, do not permit the existence of harmonics other than odd integral multiples of the fundamental frequency, *i.e.*, 3rd, 5th, 7th, 9th, 11th, etc., harmonics. Such harmonics may exist in either or both the current and voltage waves of a power system.

Commercial frequencies of power transmission in California are 25, 50 and 60 cycles per second. The power systems, so far investigated, operate at a fundamental frequency of 60 cycles per second. The investigation has shown harmonic currents and voltages of appreciable magnitude up to the 35th harmonic. On one system the 23rd (corresponding to a frequency of 1380 cycles per second) has been found to be prominent. Induced currents and voltages in parallel communication circuits have been observed corresponding to these harmonics.

The detrimental effect of the induced voltages and currents in parallel communication circuits depends, in general, upon their magnitude and upon the frequency of the induction as compared with the operating frequency of the communication circuit. The presence of extraneous current of a frequency approaching that of normal operating frequency of the communication circuit has a more injurious effect than the same amount of current of a frequency far removed from the operating frequency of the circuit.

The frequency of the voice currents flowing in a telephone circuit ranges from about 200 cycles per second up to possibly 2000 cycles per second. The average voice frequency is considered to be approximately 800 cycles per second, and at about this frequency the telephone receiver is most sensitive. It is on account of these considerations that extraneous currents of the higher frequencies, arising from the harmonics of a power system, are relatively more detrimental to telephone service. The harmonics of the power systems have been found to be responsible for the greater portion of the inductive interference to telephone service, under normal operating conditions of parallel power circuits. Any extraneous current of a frequency within the audible range produces a disturbance which impairs the efficiency of a telephone circuit. The combined effects of all extraneous currents present, of frequencies within the range of audition, constitute the humming "noise" heard in the receiver of a telephone circuit which is subject to induction.

The effect of currents of the fundamental frequency (60 cycles or less) on telephone circuits is relatively unimportant as compared to that of higher harmonics, owing to the fact that the fundamental approaches the lower limit of audible frequencies. However, if the induction due to the fundamental becomes sufficiently great, constituting a physical hazard, or of such magnitude as to operate the protective devices on the

telephone circuits or interfere with superimposed telegraph service or other grounded signaling devices, it is then of great importance from the standpoint of interference.

In regard to the effect of extraneous currents on the operation of telegraph circuits, for reasons analogous to those given above, such circuits are relatively more affected by extraneous currents of fundamental frequency or of the frequencies corresponding to the lower harmonics such as the 3rd and 5th.

At the present time the American Telephone and Telegraph Company is undertaking, on behalf of the Joint Committee on Inductive Interference, an extensive series of tests in regard to the detrimental effect of extraneous currents of various frequencies on the intelligibility of telephone conversation. In addition, this company, in conjunction with the Western Union Telegraph Company and the Postal Telegraph Cable Company, is undertaking an investigation of the effect of extraneous currents on the operation of telegraph circuits and apparatus of different types.

Harmonic currents and voltages in power circuits arise from many causes. Generators or other rotating machines do not, in general, produce pure sine waves of fundamental frequency. This is due to several features in the design of the apparatus. A certain amount of distortion of wave form, with the consequent introduction of disturbing harmonics, is inherent with the use of transformers. This distortion of wave form is due to hysteretic action in the iron core of the transformer. The distortion varies in character and magnitude with the saturation and characteristics of the iron employed. Certain connections of transformers are possible which will suppress the third harmonic and its multiple in a three-phase power system. The fact that practically all inductive interference to telephone circuits is due to the harmonic currents and voltages, renders it important that an effort be made to obtain rotating machinery for use in power systems which produces as nearly as is reasonably possible pure sine waves of fundamental frequency, and also that an effort be made to obtain transformers and to arrange connections of the same in such a manner as to reduce as far as practicable the distortion of wave form.

APPENDIX II

Balanced and Residual Voltages and Currents

This appendix comprises the four following sections:

1. Analysis of Voltages and Currents and Discussion of the Effects of their Components.
2. Causes of Residual Voltages and Currents.
3. Means for Preventing or Reducing Residual Voltages and Currents.
4. Discussion of Tests.

1. *Analysis of Voltages and Currents and Discussion of the Effects of their Components*

To facilitate the analysis of inductive effects in parallel communication circuits, arising from a power circuit, the voltages and currents of the power circuits can be conveniently regarded as consisting of components which exhibit distinct characteristics and which may be treated separately.

Considering a three-phase circuit having equal voltages between any two conductors, the voltages to ground from the conductors can be resolved into two sets of components, balanced components and residual components. Since the voltages between any two conductors are equal, the voltages between the conductors may be graphically represented by three vectors forming an equilateral triangle. The potential of the ground may be represented by a point which may be inside or outside of the triangle, depending on the magnitude and character of the residual voltage, and the actual voltages to ground from the conductors may be represented by three vectors drawn between the point representing the ground potential and the corners of the triangle. The balanced components of the voltages to ground from the conductors consist of three equal voltages whose vector sum is zero and which are therefore displaced one-third cycle in time phase with respect to one another. These balanced components may be represented by three vectors drawn from the center of the equilateral triangle to the corners. The residual components of the voltages to ground from the conductors consist of three equal voltages which are in phase with one another and which may be represented by three identical vectors drawn from the point representing the ground potential to the center of the equilateral triangle. If the residual voltage is zero the point representing the ground potential will be at the center of the triangle. The residual voltage of the

system is defined as the vector sum of the voltages of the three conductors to ground. It is therefore, by definition, three times the residual voltage of the individual conductors, or three times the equivalent single-phase voltage of the three conductors in parallel with respect to the earth. It should be noted that the inductive effect of the residual voltage is equal to that of a single-phase voltage between ground and the three conductors in parallel equal to the residual voltage of the individual conductors or to one-third the residual voltage of the system.

If one conductor is grounded the residual components (assuming the voltages between wires remain unchanged) will each equal the voltage between conductors divided by the square root of three, and the residual voltage of the system will be equal to the voltage between conductors multiplied by the square root of three.

If a power circuit consists of a single conductor with ground return, the residual voltage will be equal to the voltage from the conductor to ground.

The currents flowing in the three wires of a three-phase, three-wire circuit can be considered to be composed of three sets of currents; namely, (1) balanced components consisting of equal currents in each of the three line wires whose vector sum is zero, and which are, therefore, displaced one-third cycle in time phase with respect to one another; (2) a single-phase current flowing in a loop composed of two of the line wires; (3) a residual current divided equally between the three line wires and returning through the earth. The residual current of the three-phase circuit is defined as the vector sum of the three line currents. It is, therefore, the equivalent of a single-phase current through the three line conductors in parallel, with the earth completing the circuit.

In the case of a power circuit consisting of a single conductor with a ground return the entire current flowing in the conductor is residual.

In the above discussion, reference is made to three-phase, three-wire power circuits, but the analysis there given may be generalized so as to apply to a power system of any number of phases. Most electrical power transmission systems are of the three-phase, three-wire type and subsequent statements will apply particularly to such systems, unless otherwise stated.

At a point in the vicinity of a power circuit, such as might represent the location of an element of a communication circuit

conductor, the resultant electromagnetic field due to the balanced currents would be zero if the power circuit conductors were equidistant from the point (disregarding the effect of the earth). In general, the power circuit conductors are not exactly equidistant from such point, and therefore the resultant electromagnetic field due to balanced currents is not zero. For this reason, the balanced currents in the power circuit have unequal effects on the communication circuit, hence there is a resultant induction. For residuals, there is, in general, a much greater inequality in the distances between the affected conductors (or circuits) and the sides of the residual circuit (power conductors in parallel one side, earth other side) than in the distances to the several power conductors, which constitute the circuit for the balanced components. Thus the resultant electromagnetic field due to residual currents is large in comparison with the field set up by balanced currents of the same magnitude. It may be noted that the electromagnetic forces at any point due to residual currents in the different power conductors are in the same time phase, hence the inductive effects of all the residual components are cumulative and not differential as in the case of the balanced components.

In a similar way it may be shown that residual voltages produce proportionately far greater inductive effects than balanced voltages.

Computations based on the physical characteristics of two of the parallels investigated show that, for an exposure near Salinas for eight miles with a 55,000-volt line on the opposite side of the county road from a communication line, one ampere of residual current produces as much induction in a ground return communication circuit as would forty amperes of balanced current; and one volt residual produces as much induction as one hundred and ten volts balanced. Similar computations based on the physical characteristics of an exposure between Santa Cruz and Watsonville, where the communication circuits are paralleled for seventeen miles by a 22,000-volt line on the opposite side of the county road, show that one ampere residual produces as much induction in a ground return communication circuit as would two hundred and forty amperes of balanced current; and one volt residual produces as much induction as twenty-five volts balanced. All of the above comparative values are for current and voltages of 60 cycles frequency.

The above values illustrate the relative induction-producing

powers of balanced and residual currents and voltages in two specific cases. Such values will vary considerably for different parallels, but these cited may be taken, in a general way, as indicative of the relative severity of the effects on a single conductor produced by these two factors. Such values for a unit length of non-transposed circuit in any given parallel, are dependent upon the separation, height, and configuration of the conductors of the two classes of circuits, and upon the character and condition of the ground and neighboring objects. For the entire parallel, or total length of exposure, these values are further dependent upon transpositions. The actual amount of induction arising from each of the two components depends also upon the actual magnitudes and the frequencies of the components in the power circuit.

It will be shown in Appendix III that inductive interference arising from balanced currents and voltages can be reduced by proper transpositions in the power circuit, but that power circuit transpositions do not reduce the inductive interference produced in a parallel communication circuit by residuals. Residual currents and voltages act inductively to produce the same effects as a single-phase grounded circuit operating with the three line conductors in parallel. This generally represents the worst possible condition from the standpoint of inductive interference. Transposing the conductors of the power circuit cannot reduce the inductive interference arising from residuals, except in so far as the magnitude of the residual voltages and currents is reduced by such transpositions. The effect of power circuit transpositions on the magnitude of these components is discussed below.

In the detailed discussion of transpositions in Appendix III it is shown that transpositions in a communication circuit can reduce the induced voltages from residuals only as between the two sides of a metallic circuit.

In view of the above it is evident that attention must be given to the problem of restricting residuals to amounts which do not cause material interference either to grounded communication circuits or to properly transposed and balanced metallic circuits.

2. *Causes of Residual Voltages and Currents*

While a degree of balance of the voltages and currents of the power system may be obtained which satisfies all the practical demands of power operation, this may not be sufficient to prevent the production of residuals sufficient to cause serious inductive interference to parallel communication circuits.

Residual currents and voltages may arise from one or more causes which act singly or together. The principal sources of residual currents and voltages are:

1. Unbalanced loads between the three phases and the neutral of a grounded star-connected system.
2. The introduction of the third harmonic and its odd multiples as residual current and voltage due to certain apparatus and connections employed on a grounded star-connected system.
3. Unbalanced capacity and leakage between the several phases of the system and ground. This applies more particularly to systems isolated from ground.

There are two principal types of commercial three-phase power circuits used in California:

1. The grounded neutral circuit or network in which all important generating points have a grounded neutral and in which all or part of the receiving points may be connected with a grounded neutral. No resistances are inserted between the neutrals and ground.
2. The isolated circuit or network which normally has no metallic connection to ground at any point.

The characteristics of the grounded neutral system with particular reference to residuals are as follows:

Under Normal Conditions.

(a) The impedances between line conductors and ground are determined very largely by the load impedances of the transformers. With balanced loads the residual voltage other than the third harmonic and its odd multiples may be eliminated.

(b) The effect of unbalanced loads on the residual voltage is small, as the tendency of generators and transformers is to maintain equal voltages between the several conductors and ground.

(c) With balanced loads the residual current, other than the third harmonic and its odd multiples, may be eliminated.

(d) Unbalanced loads between line and neutral cause corresponding residual currents, which will be large if the unbalance is large, as such unbalanced load currents flow through the neutral to earth.

(e) The varying permeability of the iron in star-connected transformers with grounded neutrals introduces the third harmonic and its odd multiples as residual voltages and currents. The use of delta-connected secondary windings reduces this effect greatly below that of star to star connections.

(f) Grounded star-connected generators connected directly to the line or through grounded star to star-connected banks of

transformers, may introduce the third harmonic and its odd multiples as residual voltages and currents.

Under Abnormal Conditions

(g) A ground on one phase short-circuits that phase through the neutral connection and causes a residual current throughout the whole length of the circuit, this current being practically equal to the short-circuit current to ground on that portion of the circuit between the sources of power supplying the fault and the point where the circuit is grounded. A large residual voltage (approaching as a maximum 58 per cent of the voltage between phases) will be created in proximity to the fault, and, if the low-tension side of the receiving transformers is star-connected, throughout that portion of the circuit between the fault and such receiving transformers. If the neutral of the receiving transformers is isolated, the short-circuit current will exist only between the source of supply and the fault and there will be no residual current between the fault and such receiving transformer. The above-mentioned residual voltage will in this case exist not only in proximity to the fault on the supply side but also throughout the length of circuit from the fault to the receiving transformers. The power circuit is rendered inoperative.

(h) An open condition of one phase causes a large residual current, as the unbalanced load currents of the other two phases must flow through the neutral to earth. A large residual voltage will exist beyond the fault if the low-tension side of the receiving transformers is star-connected. The power circuit may not be rendered inoperative for three-phase supply beyond the fault, in case the receiving transformers are grounded star-delta connected.

The characterisitics of the isolated system with particular reference to residuals are as follows:

Under Normal Conditions

(a) The impedances between line conductors and ground are determined by the electrostatic capacities and the leakage between the several conductors and ground. With balanced loads a residual voltage may exist due to unbalanced capacity and leakage. Such residual voltage as is due to unbalanced capacity may be eliminated by transposing the circuit so as to equalize the electrostatic capacities to ground of the several phases. If there are single-phase branches making the total lengths of the three conductors unequal, this will introduce

inequalities among the capacities to ground which it may not be possible to balance by transpositions. Inequalities in capacity or leakage result in unequal voltages between the different line conductors and ground.

(b) The effect of unbalanced loads on the residual voltage is very slight.

(c) With balanced loads a small residual current consisting of unbalanced charging current may flow, due to non-uniform distribution of unbalanced capacity and leakage.

(d) Unbalanced loads have but a slight effect upon the residual current.

(e) The transformers cannot introduce the third harmonic and its odd multiples as residual voltages or currents.

NOTE: Due to unsymmetrical three-phase connections sometimes employed (such as open-delta and Scott connections) the third harmonic and its odd multiples may appear in the voltages between lines and in the line currents, creating dissimilarities in the wave forms for the several phases. These harmonic components of the line voltages and currents are affected by unbalanced capacity and leakage in the same way as any other components as may appear in the residuals. It should be noted, however, that such harmonics are not impressed directly upon the line as residuals as is the case with grounded neutral systems.

(f) The generators cannot introduce the third harmonic and its odd multiples as residual voltages and currents.

NOTE: If a two-phase generator containing a third harmonic in its voltage wave supplies the line through Scott or other two- to three-phase transformer connections the third harmonic will appear in the voltage between lines. Subject to the conditions of the circuit as regards capacity and leakage balance, this harmonic along with all others may or may not appear in the residuals.

Under Abnormal Conditions

(g) A ground on one phase causes a large residual voltage (173 per cent of the voltage between phases) throughout the entire length of the circuit. A residual current will be created in proximity to the fault, its magnitude increasing with the extent, voltage and frequency of the system. The power circuit may not be rendered inoperative and the power company operators may be unaware of the existence of the abnormal condition. In some cases the residual voltage and current are greatly augmented by the resonant effects accompanying arcing grounds.

(h) An open condition of one phase may cause a large residual voltage, a certain amount of residual current will flow, due to the interchange of unbalanced charging current, between sections

of line on either side of the fault. The power circuit is rendered inoperative for three-phase supply beyond the fault.

A consideration of the characteristics of the two types of systems indicates that under normal operating conditions, with balanced loads upon all phases, the residuals of the grounded neutral system may be limited to the third harmonic and its odd multiples. The magnitude of these harmonics is dependent largely on the type of connection on the low-tension side of the transformer banks, the delta being preferable to star connection. Under the same condition the residuals of the isolated system may be limited to those resulting from unbalanced leakages to ground, which should be small on a well-maintained system. The effect of an unbalance in the loads connected between conductors upon the residuals of either type of system is small, while the effect of an unbalance in the loads connected between conductors and ground upon a grounded neutral system is to cause a residual current which is proportional to the amount of such unbalance, which will be large if the unbalance is severe. The residual current due to this cause, consists of the fundamental and all harmonics present in the line currents, in addition to which the third and its odd multiples are introduced as before by the varying permeability of the transformer iron, and in some cases by the generators.

Under abnormal conditions both types of systems give rise to residuals which are liable to cause interruption and damage to parallel communication circuits. The most frequent abnormal condition which produces severe interference is an accidental ground. A ground on one phase of a grounded star-connected system creates a severe and wide-spread electromagnetic unbalance, giving rise to corresponding inductive effects. This is accompanied by an electrostatic unbalance in the vicinity of such ground. On the lower voltage systems this latter effect is relatively of little importance. On the other hand, a ground on one phase of an isolated system creates a severe and wide-spread electromagnetic unbalance, giving rise to corresponding inductive effects. This is accompanied by an electromagnetic unbalance in the vicinity of the ground. On small low-voltage isolated systems, such electromagnetic unbalance is relatively of little consequence, but it should be noted that with increased voltage and extent of the system such effects do become of great importance, giving rise to electromagnetic disturbances in exposed communication circuits in addition to the electrostatic disturbances.

The magnitude of the inductive effects from either type of system is dependent upon the character of the exposure, extent of the power circuit and other factors which render it impossible with the information at hand to draw a definite conclusion as to the relative total amounts of interference inherent with the two types of system. Furthermore, it is not necessarily true that either type of connection has an advantage from the inductive interference standpoint for power systems of all sizes and voltages.

3. *Means for Preventing or Reducing Residual Voltages and Currents*

To minimize or prevent residual voltages and currents due to cause 1, it is necessary to equalize as closely as practicable at all points the load between the several phases of the circuit and the neutral, or to remove the ground path for unbalanced load currents, thus allowing a grounded neutral at one end of the circuit only. As it is difficult, if not impossible, to maintain all loads in a state of equilibrium at all times, the latter method has the advantage of greater reliability.

Single-phase connections to ground should not be employed. Where single-phase loads or unbalanced three-phase loads must be supplied, the transformers supplying such loads may be connected across the line wires, or may be connected star to delta, with the neutral not grounded. It should be noted that single-phase or unbalanced three-phase loads on the low-tension or delta side of grounded star to delta-connected transformers produce effects on the high-tension side similar qualitatively to single-phase loads between line and ground, but these effects are greatly reduced in magnitude by the inherent balancing influence of transformers so connected, due to the fact that all three transformers participate in supplying such a single-phase load.

Residuals which arise from cause 2 may be greatly reduced by means of certain types of connections for generators and transformers. Thus for example, connecting the secondary windings of the transformer banks in delta largely suppresses these components of the residual voltage and current but does not entirely prevent them. Where the transformers are connected grounded star to star, these components can be, to a certain extent, kept out of the line by the use of a second bank of transformers having a delta connection on one side and a star connection on the side in common with the first bank, with the neutrals interconnected.

The possibility of the introduction of third-harmonic residuals

on the line due to the use of grounded star-connected generators may be avoided by the employment of transformers between generators and line, the windings on the generator side of the transformers being isolated from ground.

To eliminate or reduce residual currents and voltages which may be due to cause 3, it is necessary to transpose the conductors of the power circuit so as to equalize the electrostatic capacities of the several phases to ground, and this equalization must be attained within distances sufficiently short to prevent the accumulation of large unbalances. With a horizontal arrangement of conductors, the capacities to ground are more nearly equal that with the triangular or vertical arrangement. It is probable that the electrostatic capacities are the controlling factors in determining the residual voltage and current of an isolated system under normal operation, and while an investigation of the extent to which such residuals may be reduced by properly spaced transpositions has not yet been made, it is reasonable to suppose that transpositions will be substantially effective. The effect of unbalanced leakage cannot be controlled, except through proper construction and maintenance of the power system. It is to be noted that the maintenance of the system free from accidental grounds and partial grounds becomes increasingly difficult the larger the extent of the power network.

On a grounded star-connected system, the electrostatic capacity and the leakage of the several phases to ground are relatively less effective in producing residual voltage, as on such systems the voltages to ground are determined almost entirely by the generators and transformers.

4. *Discussion of Tests.*

Having given a general analysis of the causes and effects of and means to reduce residual currents and voltages, it is desirable to call attention to the results of tests which have been conducted, which have a bearing on this subject.

At Salinas, the effect of grounding or isolating the neutral of the auto-transformers, which have also a secondary delta winding, was investigated. These auto-transformers are supplied at 55,000 volts over a transmission line which parallels the circuits of The Pacific Telephone and Telegraph Company in what have been termed exposures No. 1 and No. 2. These auto-transformers in turn supply a 33,000-volt line of the Coast Valleys Gas and Electric Company, extending from Salinas to King City,

a distance of approximately 45 miles, and paralleling throughout practically this entire length, the coast route toll lead of The Pacific Telephone and Telegraph Company. These same telephone circuits are involved in the parallels with the 55,000-volt line north of Salinas. In addition to supplying the King City line this bank of auto-transformers at Salinas supplies a 22,000-volt line extending to Monterey, a distance of approximately 18 miles. Aside from the ground on the transformer neutral at Salinas, there are no grounds on either the 33,000-volt line or the 22,000-volt line. The 55,000-volt line supplying the Salinas transformers is energized at the Guadalupe substation of the Sierra and San Francisco Power Company, approximately 73 miles distant from Salinas, through grounded star-connected auto-transformers, which have delta-connected secondary windings, and which are supplied by the 104,000-volt line of this same system which operates with grounded neutral connection at its main generating station and substations. It will be understood from this statement of conditions that the neutral current at Salinas is not identical with the residual current of any one of the three high-tension lines which are connected together by these auto-transformers. The condition of the Salinas neutral affects the induction arising from the several exposures through its effect on the residual currents and voltages of the high-tension lines connected to the auto-transformers at that point. A representative value of the neutral current at Salinas during these tests is 0.3 ampere. It is composed almost entirely of the ninth harmonic, the fundamental and the third harmonic, their magnitudes decreasing in the order named. With the power system in normal operation, isolating the neutral of the auto-transformers at Salinas did not greatly affect the resultant induction in the particular exposures under observation. The values in the following table, taken from the data of the tests, indicate the effect of the condition of this neutral on the residual currents of the 55,000-volt and the 33,000-volt lines.

RESIDUAL CURRENT AT SALINAS—AMPERES.

Order of Harmonic	55,000-volt line.		33,000-volt line.	
	Neutral at Salinas		Neutral at Salinas	
	Grounded	Non-Grounded	Grounded	Non-Grounded
1	0.120	0.057	0.061	0.073
3	0.054	0.160	0.075	0.120
9	0.073	0.100	0.120	0.075

Two reasons may be given for the fact that the condition of the Salinas neutral does not greatly affect the resultant residual current of these lines: (1) the load balance on these lines is such that a relatively small amount of load current flows through this neutral: (2) as three high-tension lines are connected together by these auto-transformers, opening their neutral connection to ground does not completely eliminate the path for the residual current of any one of the three lines, since it may then flow to earth through the admittance to ground of the other two lines.

These particular conditions are not commonly found, but a similar condition, in that there is a path to ground for residual current aside from the neutral connection, prevails in any case where the power circuit extends for a considerable distance beyond such neutral connection. The investigation showed, for the conditions which applied to the 55,000-volt line, that removing the neutral ground connection beyond the parallel decreased the fundamental and increased the third and ninth harmonics in the residual current as shown in the above table. It is not be concluded, however, from this one case, that the third harmonic and its odd multiples in the residual current would in all cases be increased by removing the neutral ground connection of a bank of receiving transformers where the circuit extends beyond the point of measurement of such residual current. If the circuit is terminated at the transformer bank, the removal of the neutral ground connection must eliminate the residual current at that point.

In the case of the 33,000-volt line, the grounding of the neutral at Salinas merely gave another and nearer grounded neutral point on the line supplying power but did not give a grounded neutral point in each direction from the point of measurement of the residuals as it did in the case of the 55,000-volt line. As the 33,000-volt line has no grounded connection beyond Salinas, the residual current must flow to ground entirely through the admittance of this line to ground. The residual current, therefore, diminishes to zero at the King City end of the line. Isolating the neutral of the Salinas transformers affects the constituents of the residual currents in this line arising from the Salinas transformers, and those impressed by the 55,000-volt line, in such a way that they combine vectorially to give a different resultant from that with the Salinas neutral grounded. The result is to increase the fundamental and third harmonic and to decrease the ninth harmonic when the neutral is isolated. The residual current in the 22,000-volt

line was not determined, but residual voltage measurements were made with the Salinas neutral isolated and grounded and the results are included in the following table, from which it may be noted that the fundamental, third and ninth harmonics were all greater with the Salinas neutral isolated.

The banks of star-connected auto-transformers at the Guadalupe and Salinas substations are provided with closed-delta secondary windings, which in the case of Salinas supply power for local consumption. An experimental opening of the delta at Salinas demonstrated, as would be anticipated, that the use of such delta-connected secondary windings reduces, in a large measure, the third harmonic introduced by these transformers in comparison with its value without the use of such delta-connected windings. If grounded star-connected transformers are used, it is important, therefore, from the standpoint of induction, to provide such transformers with closed-delta-connected secondary windings or with other means of reducing the third harmonic and its odd multiples. Such means may, however, in some cases be insufficient to reduce the residuals to such low values that they will not produce harmful inductive interference to parallel communication circuits.

The investigation on the system of the Coast Counties Gas and Electric Company shows results which are summarized in the following table with reference to the residual current and residual voltage. Santa Cruz, where the measurements were made, is 20 miles from one source of supply and 75 miles from the other end of the line, where power was also supplied. For the sake of comparison the averages of the residual voltage of the 22,000-volt line between Salinas and Monterey, a distance of 18 miles, are also given:

Order of Harmonic	Residual Voltage—volts.			Residual Current amperes
	Santa Cruz	Salinas Neutral		Santa Cruz
		Grounded	Non-Grounded	
1	360	50	90	0.094
3	—	150	320	—
9	19	40	50	0.021
11	14	—	—	0.017
13	10	—	—	—
23	14	—	—	—

The system of the Coast Counties Gas and Electric Company is isolated from ground and employs a number of Scott-connected and open-delta-connected transformers. The residuals at Santa Cruz on this system are composed principally of fundamental, ninth and eleventh harmonics. The fundamental is predominant. The third harmonic is absent or too small to measure accurately. It should be noted here that the use of Scott- and open-delta-connected transformers permits the third harmonic and its odd multiples to exist in the line voltages and currents of a three-phase isolated system. In all probability the residuals on this system are caused by unbalanced admittances to ground of the power line conductors. As has already been pointed out, that part of the unbalance due to electrostatic capacity could be greatly reduced by properly spaced transpositions in the power circuit. In contrast to the results at Salinas, the residuals of this system exhibit a prominent fundamental and the absence of, or relatively small amounts of, the third harmonic and its odd multiples.

APPENDIX III

Transpositions

The sources of the disturbances in communication circuits, which arise from parallel power circuits, have been treated in the first section of the preceding appendix. The effect of transpositions on the induction in communication circuits produced by parallel power circuits will now be considered.

This appendix comprises the four following sections:

1. Effect of Transpositions in Reducing Induction.
2. Characteristics of Present Transposition Systems.
3. Characteristics of Proposed Transposition Schemes.
4. Results of Tests.

1. *Effect of Transpositions in Reducing Induction.*

Transposing a circuit is the interchanging of the positions occupied by the conductors.

By transposing a power line the phase of the resultant electromagnetic field due to balanced currents and the phase of the resultant electrostatic field due to balanced voltages is changed, and the induction is reduced by the production of neutralizing effects in the neighboring lengths of a parallel conductor. Thus, by locating the power circuit transpositions so that each conductor occupies all of the several possible conductor positions

for equal distances, a section or "barrel" is obtained within which the resultant induction on a parallel conductor due to balanced currents and voltages is completely neutralized, neglecting attenuation and remanent electrostatic effect and assuming the parallel is uniform throughout the barrel.

Inasmuch as residual currents and voltages are in phase in the several conductors, the transposition of the power circuit does not reduce the inductive effects therefrom in a parallel conductor, except as the magnitudes of the residual currents and voltages are reduced by the power circuit transposition. (See Appendix II).

As usually constructed, the conductors of a telephone circuit are close together as compared with their distances to a power line, and the circuit is usually isolated from ground. Could the conductors of a metallic communication circuit be located at the same point in space, as is approximately true of a pair of wires twisted together, the resultant electromagnetic and electrostatic induction between the sides of the communication circuit would be zero. The voltage induced along the conductors of the telephone circuit and the induced voltage to ground would be present but would not be effective in producing any voltage between the conductors of the telephone circuit, provided the capacity and leakage to ground of each side of the telephone circuit were equal. On overhead lines the conductors of a metallic communication circuit must be at least several inches apart, hence in general when paralleled by a power line, the resultant electromagnetic and electrostatic induction in the two conductors will be unequal in magnitude. The result is that a voltage exists between the sides of the circuit which causes a current to flow in apparatus connected between the conductors, such as a telephone receiver.

Transpositions in communication circuits tend to equalize the induction in the two sides of the circuits by exposing each side equally to the influence of the power circuit, that is, by reversing in successive lengths the phase of the induction between the two sides of the circuit.

In an exposure where the induction from unbalanced currents and voltages would be completely neutralized by the power circuit transposition system if there were no communication circuit transpositions, or where such induction would be completely equalized by the communication circuit transpositions if there were no power circuit transpositions, this induction will practically

always be partially cumulative if both power and communication circuit transpositions are installed without due reference to each other. It should be noted, however, that the maximum disturbances which may be set up in a parallel communication circuit by balanced currents and voltages in the power circuit will be present when neither the power circuit nor the communication circuit is transposed. Hence it is very important that the power and communication circuit transpositions be properly located with respect to each other and in this way only can the maximum benefits from the transposition be derived.

Induction from residual currents and voltages is reduced by communication circuit transpositions.

If the communication circuit has a ground return, it cannot be transposed and the power circuit transpositions alone will be effective in reducing interference arising from the balanced currents and voltages. Also, the induction into a ground return communication circuit from residual currents and voltages is not affected by transpositions, except indirectly, as previously stated. It is possible, though not of general practical application, to obtain the effect of a transposition in a grounded alternating-current power or communication circuit by means of a transformer or repeating coil.

Induction between wires and ground is harmful to metallic as well as to ground return circuits, for in case the metallic circuit is not perfectly balanced electrically, such induced voltage forces a current to circulate in the metallic circuit through the terminal apparatus. It is not practical to maintain communication circuits in a state of perfect balance at all times.

2. *Characteristics of Present Transposition Systems.*

The transposition systems used on long distance metallic telephone circuits are designed primarily to reduce the "cross-talk" or induction from one telephone circuit into another and provide for a high degree of balance between any circuit and all others on the line.

The length of standard balanced telephone transposition sections used by The Pacific Telephone and Telegraph Company is approximately eight miles (more exactly, 41,600 feet), and this is representative of the length of sections of the transposition systems used by other companies operating similar lines. To improve the transmitting qualities of telephone circuits used for long distance work, loading coils are introduced in certain circuits at the ends of the standard transposition sections. Uniform

spacing of the telephone "S" poles (end poles of transposition sections) is an important consideration in the application of loading. It is important that the induction be neutralized in each section between loading points, as these are points of discontinuity in the circuits.

The system now used also provides for the transposition of every circuit at actual intervals ranging from one-quarter mile to two miles, the average intervals for different circuits varying from approximately one-quarter mile to three-quarters of a mile, hence every circuit is to a certain extent balanced to induction from parallel power circuits.

In addition to the metallic circuits composed of two conductors, the telephone companies employ phantom circuits which are made up from two physical (two-wire) circuits. Each "conductor" or side of the phantom circuit consists of the two conductors which form one physical circuit. As usually made up, the physical circuits occupying adjacent horizontal positions are used for the phantom circuit. Hence, the average distance between the sides of the phantom circuit is equal to twice the distance between the conductors of the physical circuits. Due to the greater distance between the sides of the phantom circuit as compared with the physical circuits, the phantom circuits are more subject to inductive interference than the physical circuits. The phantom circuit possesses marked advantages in economy and transmission efficiency over the physical circuits composing it, hence, is extensively used for the longer distances. The transpositions in the phantom circuits are spaced at average intervals, for different circuits, varying approximately from three-quarters of a mile to two miles.

The purpose of transposition systems applied to power circuits has been to reduce the disturbance in parallel communication circuits and in some cases to equalize the separation of the pairs of conductors forming the several phases. Usually when transpositions have been applied to power circuits to reduce the disturbance in existing parallel communication circuits, one or more complete barrels have been provided within the total length of the exposure. The best obtainable results from power circuit transpositions will be had only when they are located with due regard to the transposition points of the communication circuit. No such practise as this has been followed in the past. The transposition systems heretofore applied to parallel power and communication circuits have therefore failed to meet

the requirements for maximum effectiveness. Hence, balanced currents and voltages in the power circuits have, in general, caused more disturbance than necessary in parallel communication circuits.

3. *Characteristics of Proposed Transposition Schemes.*

It would be possible to fulfill the conditions for balance with regard to induction arising from balanced currents and voltages, by cutting a " barrel " into the power circuit between successive communication circuit transpositions. Inasmuch as telephone transposition points are ordinarily spaced at one-fourth mile intervals, this solution in the case of a three-phase power circuit would necessitate transpositions at an average spacing of one-eighth mile and a minimum spacing of one-twelfth mile, which is impracticable in most cases.

It would be possible to satisfy the conditions for balancing the induction in metallic circuits, from both balanced and residual currents and voltages, by installing any completely balanced system of communication circuit transpositions between each two successive power circuit transpositions. Assuming twelve-mile " barrels " in the power circuit, the conditions for balance could be fulfilled with the present standard telephone transposition system. However, with power circuit barrels of a length such as is essential in most parallels, this solution would require the redesign and relocation of all telephone transpositions in the exposure, involving several times as many transpositions as are normally require, with the liability of interference with the location of loading coils.

Both the above solutions satisfy the conditions for balancing the induction in metallic circuits, arising from residuals, in a length of circuit equal to twice the distance between successive communication circuit transpositions, assuming these are uniformly spaced. In the standard transposition section as now used, balance is thus obtained in distances varying from an average of approximately one-half to four miles.

Between these two comparatively simple but extreme solutions the practical but more complicated solution for general cases is to be obtained. This involves the combination of power circuit barrels of moderate length with a modified communication circuit transposition system designed to procure balance as far as practicable for all circuits. In this way coordinated transposition systems may be designated which are sufficiently flexible

to meet the requirements of short parallels and portions of longer parallels separated by points of discontinuity.

In the discussion above with reference to schemes of transpositions, the balances or unbalances mentioned are those which would occur, due solely to the relative locations of transpositions, in an exposure whose physical characteristics are uniform throughout. Even with a scheme of transpositions, balanced in the sense described, applied to both power and communication circuits involved in an actual parallel, there are a number of factors as noted below, which in general are not capable of being taken into account quantitatively and because of which effective neutralization may not be obtained. These factors are:

1. Non-uniformity of separation, configuration and other physical characteristics.
2. Variation in magnitude and phase of the inductive effects along the exposure (applying particularly to the higher frequencies.)
3. Inherent inability of transpositions to completely neutralize electrostatic induction (this remanent effect can be reduced as far as desired by inserting a sufficient number of transpositions.)
4. Imperfect electrical balance of the communication circuit.

While these factors which prevent complete neutralization of the induction cannot be entirely eliminated, their effects can be abated by reducing the length of balanced transposition sections. Thus it is not sufficient merely to install transpositions in both lines so that they are balanced to each other, but, also, it is necessary to take into consideration the length of section within which balance is obtained and to make this length as short as the conditions of the particular case require.

Points of discontinuity, such as abrupt changes in power line current where a material amount of load is taken off, cross-overs, or substantial changes in separation, should, if practicable, be made neutral points (junction points of balanced sections) in the transposition scheme. Where cross-overs occur balance should in general be obtained independently for the portions of the communication line on each side of the power circuit.

The transposition system and the location and spacing of transposition poles are factors of prime importance in the successful operation of telephone lines, on account of the mutual effects among the many circuits carried on such lines. On the other hand, transpositions in power circuits are, relatively, of minor importance in the operation of a power system and from this standpoint the effect of small changes in the location of such transpositions is negligible. Hence, in general, the requirements

of the communication circuits are the chief factors which should govern the location of all transpositions in both power and communication circuits.

An individual study is necessary to determine the best procedure for any given parallel, owing to the wide variation in conditions. Thus only is it possible in each case to determine the best location and method of transpositions with regard to the requirements of both power and communication systems.

4. *Results of Tests.*

The investigation at Salinas demonstrated that the induction in a ground return circuit in the exposures concerned, arises principally from the residual voltages and currents while the induction in a metallic circuit shows principally the characteristics of the balanced voltages and currents together with some effect from the residuals. This result was to be expected, as there are power circuit transpositions which reduce the induction in the conductors used as ground return circuits, due to the balanced components, but these transpositions and the transpositions in the telephone circuits are improperly located with respect to each other and therefore are inefficient as regards the induction in the metallic circuits. On the other hand, the telephone transposition system tends inherently to reduce the induction in the metallic circuits, arising from residuals. A study of the relative location of power and telephone circuit transpositions for exposure No. 2 at Salinas, indicated that by modifying the present transpositions of both circuits, it is possible to reduce materially the induction from balanced currents and voltages. Had it been feasible to take the power circuit out of service for the purpose of experimental retransposition, the above scheme, as well as one for the King City exposure, would probably have been installed and the effects thereof experimentally determined. Under the conditions existing, however, it was deemed advisable to postpone the matter of transpositions for both these exposures, pending the acquisition of further information as to the extent to which retransposition would be warranted as a permanent improvement.

The experimental study of transpositions was, therefore, transferred to another point where a power line is not the sole source of supply and can, therefore, be shut down for alterations and tests under special conditions.

The experimental determination of the practical effectiveness of transpositions has not been completed. However, an ex-

tended theoretical study of transpositions has been made, including the design of a modified telephone transposition system. This system, which requires many additional transpositions, is more flexible in its properties of coordination with different lengths of power circuit "barrels".

A study made to determine the relative efficiency of various schemes of transpositions designed for the Santa Cruz-Watsonville exposure of The Pacific Telephone and Telegraph Company's toll lead to the 22,000-volt line of the Coast Counties Gas and Electric Company, emphasizes the following general principles:

1. The necessity of proper relative location of power and telephone circuit transpositions.
2. The importance of the effect of cross-overs and the desirability of making them neutral points in the transposition scheme.
3. The necessity of some modification of the telephone transposition system.

APPENDIX IV

Apparatus

For the proper conduct of its tests and experiments the Joint Committee on Inductive Interference has secured, either through purchase or on loan account from various power and communication interests, apparatus of an aggregate value of over twelve thousand dollars.

The following is a brief schedule of the property in use by this Committee, together with its estimated replacement value:

Buildings (Portable Laboratory)		$ 480.00
Furniture and Fixtures		128.00
Apparatus—Oscillograph	$1,115.00	
Oscillator	600.00	
Motor-Generator Set	260.00	
Meters	1,202.50	
Batteries	100.00	
Condensers	990.00	
Bridges	675.00	
Galvanometers	265.00	
Rheostats	734.80	
Switchboards	135.40	
Misc. Apparatus	1,505.00	
Coils and Relays	645.00	
Transformers	2,412.50	
Miscellaneous	787.00	
Photographic	293.60	11,820.80
Grand Total		$12,428.80

The above property is owned by the Joint Committee on Inductive Interference and various power and communication companies, as follows:

Joint Committee on Inductive Interference	$ 1,251.15
The Pacific Telephone and Telegraph Company and American Telephone and Telegraph Company	8,293.65
Sierra and San Francisco Power Company	2,002.50
San Joaquin Light and Power Company	300.00
Pacific Gas and Electric Company	110.00
Western Union Telegraph Company	235.00
Testing Force	256.50
Total	$12,428.80

APPENDIX V

List of Technical Reports

The following is a list of the technical reports which have been prepared in connection with the investigation of the Joint Committee on Inductive Interference:

Technical Report No.	Subject
1.	General outline of tests to be made at Salinas on parallels between lines of the Sierra and San Francisco Power Company, the Western Union Telegraph Company, the Southern Pacific Company, and The Pacific Telephone and Telegraph Company. (6 pages.)
2.	Summary of results of tests at Morganhill on parallel between lines of the Coast Counties Gas and Electric Company and The Pacific Telephone and Telegraph Company between Morganhill and Gilroy. (8 pages.)
3.	A description of the noise standard in use for measuring noise on telephone circuits in terms of a standard unit. (4 pages)
4.	A description of the instruments and methods used for the measurements of effective values of induced voltages and currents. (2 pages.)
5.	A description of apparatus and connections used in measuring line and residual currents and voltages of power circuits. (6 pages)
6.	Tests of the effects of opening the secondary delta of the auto-transformer bank at Salinas. (7 pages)
7.	Tests of the induction in the block signaling circuits of the Southern Pacific Company paralleled by the Salinas-King City circuit of the Coast Valleys Gas and Electric Company. (4 pages.)
8.	Tests of the induction in the telephone circuits of exposure No. 2 at Salinas under normal operating conditions of the power system, with particular reference to the effects of grounding and isolating the neutral of the Salinas auto-transformers. (16 pages)

9. Experimental determination of the coefficients of induction for residual currents and voltages in exposure No. 2 at Salinas. (4 pages.)

10. Measurements of the harmonics of the neutral current at Salinas. (4 pages.)

11. Investigation of current transformers, ratios, and errors due to the use of current transformers under the conditions of the tests. (21 pages)

12. Formulae for the computation of electrostatic and electromagnetic induction from power circuits in neighboring communication circuits. (18 pages)

13. An investigation of errors in measurements of residual voltage due to the potential transformers used and a discussion of the method of measurement at Salinas. (30 pages)

14. Comparative tests of the noise in exposed telephone circuits with power on and off the 55,000-volt power circuit of the Sierra and San Francisco Power Company between Guadalupe and Salinas. (8 pages)

15. Supplementary to Technical Report No. 8, differing from the earlier report in that the telephone circuits were shielded. Contains a discussion of transpositions. (22 pages)

16. Tests of the induction in telephone circuits exposed to the Coast Counties Gas and Electric Company's 22,000-volt line between Morganhill and Gilroy with the power circuit untransposed and open at Gilroy. (4 pages)

17. Tests of the induction in telephone circuits exposed to the Coast Counties Gas and Electric Company's 22,000-volt line between Morganhill and Gilroy, before and after installing power circuit transpositions. (24 pages)

18. Tests of the effect, on exposed telephone circuits, of grounding one phase of the Coast Counties Gas and Electric Company's 22,000-volt three-phase delta-connected line. (4 pages)

19. Test of the combined effects of the Coast Counties Gas and Electric Company's and the Sierra and San Francisco Power Company's circuits on the telephone circuits in the exposure between Morganhill and Gilroy. (4 pages)

20. Tests of the effect on the residual voltage of transposing the Coast Counties Gas and Electric Company's 22,000-volt line within the exposure between Morganhill and Gilroy. (3 pages)

21. Tests to determine the comparative effect on the noise in the exposed telephone circuits of having the power on and off the Coast Counties Gas and Electric Company's 22,000-volt line between Morganhill and Gilroy, and the effect of shielding the telephone circuit under test by grounding other circuits on the lead. (4 pages)

22. Computation of the coefficients of induction from balanced and residual currents and voltages for the telephone circuits of exposure No. 2 at Salinas. (19 pages)

23. Experimental determination of the coefficients of induction from residual currents and voltages, for the telephone circuits of exposure No. 2 at Salinas—more complete than Technical Report No. 9. (24 pages)

24. Comparison of computations of Technical Report No. 22 with experimental data of Technical Report No. 23. (16 pages)

25. Tests of induction in telephone circuits in exposure between Salinas and King City under normal operating conditions, with the neutral of the Salinas auto-transformers grounded and isolated. (20 pages)

26. Tests of accuracy of measurement of residual current by certain current transformers. (4 pages)

27. Tests of induction in telephone circuits in exposure No. 2 at Salinas with the North Beach steam station energizing the Sierra and San Francisco Power Company's line. Supplementary to Technical Reports Nos. 8 and 15, differing in the source of supply of the power system. (27 pages)

28. Supplementary to Technical Reports Nos. 8 and 15. Voltage lowered 5 per cent at the Guadalupe auto-transformers which supply the power circuit. (20 pages)

29. Determination of impedances of lines, by computations and by measurements—numerous curve sheets and tables. (65 pages)

30. Tests of induction in telephone circuits in exposure Nos. 1 and 2 at Salinas, with the neutral of the Salinas transformers grounded and isolated. (10 pages)

31. Supplementary to Technical Reports Nos. 8 and 15 and more complete. Includes tests with Salinas neutral grounded and isolated and with telephone circuits shielded and unshielded. (29 pages)

32. Supplementary to Technical Report No. 25. (22 pages)

33. Induction in test leads used at Salinas for connecting testing apparatus to the circuits of exposure No. 2 and the effect of such on the measurements of the induction from the exposure. (20 pages)

34. Effect of changes in the insulation resistance of the telephone line on the induction in telephone circuits of exposure No. 2 at Salinas. Also supplements Technical Reports Nos. 8, 15, and 31. (24 pages)

35. General outline of tests to be made at Santa Cruz on the parallel between lines of the Coast Counties Gas and Electric Company and The Pacific Telephone and Telegraph Company. (4 pages)

36. Induction in telegraph circuits of the Western Union Telegraph Company and the Southern Pacific Company in exposure No. 1 between Salinas and San Jose. (8 pages)

37. Noise tests on telephone circuits radiating from Salinas, with the neutral of the Salinas auto-transformers grounded and isolated. (4 pages)

38. General review of tests at Salinas, summarizing reports 1, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 22, 23, 24, 25, 26, 27, 28, 30, 31, 32, 33, 34, 36, and 37. (53 pages)

39. General consideration of transpositions and a study of the results to be expected from the application of various transposition schemes to the Santa Cruz-Watsonville exposure. (36 pages)

40. Method of measurement of capacity and conductance unbalances (2 pages)

41. Harmonic analysis of alternating-current waves, by oscillograph and resonant shunt. Comparison of the methods. (30 pages)

42. Investigation of the current transformers in use at Santa Cruz, to determine their ratios of transformation and suitability for residual current measurements. (35 pages)

43. Outline of tests to determine the effect of extraneous currents on the intelligibility of telephone conversation. (8 pages)

44. Induction in the telephone circuits of the Santa Cruz-Watsonville exposure and in the test leads, from sources other than the 22,000-volt line. (12 pages)

45. Induction in the telephone circuits of the Santa Cruz-Watsonville exposure under commercial operating conditions, with the original transpositions in both power and telephone lines. (15 pages)

46. Supplementary to Technical Report No. 39. A study of additional transposition schemes for the Santa Cruz-Watsonville exposure. (14 pages)

47. Computation of the coefficients of induction for balanced and residual currents and voltages for the Santa Cruz-Watsonville exposure. (11 pages)

48. Experimental determination of coefficients of induction in the Santa Cruz-Watsonville exposure, with the original transpositions. (42 pages)

49. Further experimental determination of coefficients of induction for balanced voltages, in the Santa Cruz-Watsonville exposure, with the original transpositions. (13 pages)

50. Study of the influence of various transformer connections and flux densities on the third harmonic and its multiples in a three-phase circuit. (in preparation).

DISCUSSION ON "REPORT BY THE JOINT COMMITTEE ON INDUCTIVE INTERFERENCE", SPOKANE, WASH., SEPTEMBER 11, 1914.

P. N. Nunn: The paper just presented is one of signal interest and significance. It is of unusual moment in this, that it reports both an elaborate scientific study of great technical value and also a legal adjudication of conflicting interests between two public utilities of vast economic importance.

Briefly stated, the paper reproduces a certain report to the Railway Commission of the State of California, by a committee authorized by it to investigate the subject of electrical interference by other electrical circuits with "communication" service, including telephone, telegraph and railway signal. The investigation, occupying several years, assumed the character of a research into the intricate phenomena of distant electromagnetic induction, its remote origin in the characteristics and manipulation of power apparatus and its acoustic effects upon telephone service. To present the details of the various tests, methods and apparatus employed has involved the production of fifty special reports now summarized in this general report which draws a series of conclusions and submits and discusses a proposed code of rules for the prevention of the interference in question.

As a scientific research this investigation is invaluable and marks a distinct advance in applied electrical science. In view of the economic importance of telephone and similar service, and of the probable increase in the future in the capacities and voltages of power circuits, there appears a very real and difficult problem to be met in the evolution of the respective arts. To the solution of this problem such research should undoubtedly point the way. In this sense this report deserves marked appreciation. But at this time attention is called not so much to its scientific value as to the economic and legal effects of its code of rules.

Although recognizing a conflict of interests between the respective groups of electrical industries, the investigation was conducted and the rules drawn ostensibly to meet the problem only as a scientific question of demonstrable cause and effect. Unanimously indorsed by a committee purporting jointly to represent the telephone, the railway, and the electric power interests of the state, the rules purport to be, in effect, an agreement among all parties in interest, and as such, approved and adopted by the Commission, have become the law of California. By this process the Commission is led to adjudicate the differences and legislate changes in practise from scientific considerations alone, without regard to the broader aspects of the issues involved.

The problem is much broader than that. It involves another scientific aspect as well as questions of inherent rights, of equity,

of evolution of the respective industries, and of the policy of the public toward its utilities. Moreover, the rules are not mere logical conclusions, and their full effect is not apparent from their text. Read casually, they imply a spirit of friendly cooperation toward some mutual purpose. In results, however, benefits accrue only to one interest, while burdens, even extreme hardships, are laid upon the other. Their full import appears only from careful consideration of each rule in the light of the whole seen from a mature point-of-view.

The partisan point-of-view from which these rules have been formulated is shown by their context. "Since these rules are designed for the protection of communication circuits," (Discussion of Rules, Art. IV) acknowledges that they are designed to restrain the power circuits. While the specific parties in conflict are somewhat obscured by including the railway interests as a third party and by use of the term "communication" instead of "telephone," yet Rule V in effect waives all conflict between railway and telephone interests, thus associating them and leaving the power interests alone under restraint. And while the caption "Historical," (first paragraph) in presenting the origin of this action styles it "the outgrowth of certain differences * * * * brought to the attention of the Railway Commission" instead of plainly "a complaint by the telephone lodged against the power interests," it likewise states (fifth paragraph) that this investigation, attributed to the Joint Committee, was in fact already a department of the Pacific Telephone & Telegraph Co. and of well-defined form and character before taken over by the Joint Committee, and also that it was continued (fourth paragraph) by a staff of telephone employees. It thus appears that this measure, instead of being a mutual matter or serving a mutual purpose, is in fact a telephone project from its inception to the conclusions which are formulated into the rules presented.

The specific rules, seventeen in number as grouped under caption II, may be classified as follows:

Mutual obligations respecting the spacing of power from telephone circuits; the uniformity of parallels, and the use of adequate systems of transpositions.

Specifications of power equipment, covering wave-form of generators, charging current of transformers, type and equipment of line switches, style and location of transpositions, and also requiring ammeters in grounded neutrals and the use of ground detectors

Dictation of methods in power distribution, covering balancing of loads, balancing of circuits, and methods of connecting and loading transformers.

Restrictions in operating procedure of power industries, covering line tests and the manipulation of automatics, operation with open circuits and grounds, measurements of ground currents and the charging of electrolytic arresters.

Stipulations respecting obscure power-circuit effects, requiring the limitation of residuals and the elimination of harmonics.

In discussing the individual rules, the following general considerations should be recognized.

The scope of the restrictions placed upon power interests is without tangible limit. Rule I prohibits "parallelism", which is defined as lines in such proximity "that the power circuit is liable to create inductive interference * * * *." Note the term "liable to." It is not "has" or "does" but "liable to." The question is one of degree, but no degree being even implied, the rule stands absolute. Since inductive effects are obscure and difficult of determination, the telephone interest may readily find occasion for claiming with some plausibility that almost any power circuit of the State is in parallelism to some slight degree. Where impracticable entirely to avoid parallelism, this rule makes the power circuit subject to the seventeen specific rules classified above.

For the enforcement of these rules, far-reaching power of reprisal and dictation is reserved by the telephone interest. Rule "d" successively stipulates, emphasizes, and confirms that the telephone interest "shall have the right to specify the number, type and location of transpositions" in power circuits.

Transpositions constitute the great general measure for neutralizing interference,—the last resort. They are both a hardship in expense and a menace to safety and service, and in degree both are, in general, proportional to the voltage transposed. The right to specify them, therefore, here becomes the weapon of the telephone interest against the power interests for all manner of possible shortcomings. Upon high-voltage lines and especially upon tower circuits in good telephone districts, this right carried to logical limits under these rules becomes tantamount to supreme authority. True, the telephone interest is limited as to the frequency of its use,—not oftener than one-sixth mile apart, but this very limit serves but to emphasize the length and breadth and depth of the power here grasped by the telephone interest.

None of the expense or burden of this new regime falls upon the telephone interest. Rule IV provides that "At the option of the (telephone) company * * * * any of the provisions of II and III may be waived." Since II and III comprise in effect the entire code, this provision becomes a blanket release giving the telephone interest immunity from any unwelcome involvement. Thus these rules which in effect "box" the power interests on all sides, notwithstanding their purport of cooperation, leave for the telephone interest a back door of escape always open. It thus, for instance, in paralleling a previous power circuit, could throw upon the power interest the hardship of reconstructing to conform to the rules, while itself evading through this back door any burden whatever.

Turning now to the seventeen individual rules as already classified, or rather to a few of their characteristic provisions; of those specifying characteristics of power equipment, rule

"p" requires power companies to obtain and use generators "giving, as nearly as reasonably possible, pure sine waves of voltage * * * *". Does this mean that the power companies of California are now using generators of characteristics inferior to those recognized as standard in the industry, or does it mean that electrical manufacturers must now evolve a line of generators of new design and characteristics for the special needs of California trade? Rule "q" raises a similar question as to the exciting current of transformers. Rule "j" prohibits the use of air switches which are now so generally used and from the further development of which so much is expected, while rule "h" requires the general use of oil switches "rendered automatic for short-circuits, grounds and abnormal neutral currents." This calls for a mechanism which has already been sought for many years but never yet produced and, in the opinion of many, beyond mechanical possibility.

Referring to the rules which restrict operating proecedure as now followed, rule "o" requires the charging of electrolytic arresters during the late night, while "m", regarding line testing in cases of trouble, prohibits present prevailing practise and in effect requires the development of new methods and new apparatus for the localization of line faults.

Similarly, rule "n" specifying "* * * a record of hourly measurements of the neutral currents * * *," in effect seems to require a regular corps of attendants at every point of transformation employing a ground connection.

The class of rules respecting obscure phenomena incident to power circuits is less specific, yet rule "b" requires "special consideration shall be given to the prevention or elimination of harmonics * * *." This is a problem of many years' study by engineers, manufacturers and power companies alike, the solution of which might have saved from financial failure many of the power ventures of the past decade.

Without going further at this time into the many restrictions and their ultimate effects, the above characteristic cases will illustrate the radical nature of the rules, the impossibility of their fulfilment, and the length to which they go in demanding a virtual reconstruction of the power industries to meet the telephone's demands. They express the telephone interest's demand for impracticable ideals. That the results required are in fact impracticable ideals is tacitly recognized throughout the text by the constant recurrence of such evasive expressions as "Every reasonable effort to avoid," (several times repeated), "Every effort," and such vague expressions of degree as "Closely as practicable," "Nearly as practicable," "Most reasonable possible," and "Low as consistent with good practise."

The matter of the rule regarding crossings is of quite a different nature. Rule "a," after specifying the separation between power and communication lines, continues "The only exceptions to this provision * * *" are crossings, etc., which shall be

"* * * constructed in conformity with the National Electric Light Association specifications * * * *." The specifications here referred to were themselves initiated by the telephone interests of the East and presented through a committee formed under telephone influence. At best they are but proposed specifications, since, as a matter of record, the N. E. L. A. as an organization declined to adopt or sanction them. Since this matter occasioned much dispute, it has been generally understood that the question of crossings is specifically avoided in these rules as, in fact, it is, in title, headings and otherwise in the text. But nevertheless it is covered here and most effectively. Moreover, this brief incorporation of it seems to be without the full approval or knowledge of the Joint Committee, since at least one member still asserts that "These rules have nothing whatever to do with the question of crossings." In this light its interjection here seems somewhat a "joker" on the power interests. Suggestively similar are those terms which reserve to the telephone interest the power of waiving these rules as to itself and of specifying transpositions, and which in their final effects, as already discussed, are so far-reaching.

To briefly review: As seen by the power interests, these rules are radical, without tangible limit of scope, impossible of fulfillment, demand virtual reconstruction of their methods and business, and strain toward impracticable ideals; they have been framed by the telephone interest from an utterly partisan point of view, to secure to itself supreme power of enforcement; they have been carried to enactment against the power interests, many in number, competitive and without cooperative organization, by a single nation-wide monoply of vast coordinate resources, in California, as a first step toward similar rules wherever possible.

In conclusion: in the matter of electromagnetic interference there unquestionably is a very real and significant problem to be worked out theoretically by precisely such methods as those here reported. But then the same problem must again be worked out in practise through advance in apparatus and methods. Again the problem lies no more with the cause and its removal than with effects and their prevention; it embraces both. Moreover, by its very nature the problem primarily is that of the complainant, and its solution should first be sought at home. Thus there is force in the current retort of the power interests to the complaints of the telephone interest, that the latter has done as little to protect itself as the power interests have done to protect it. The final solution may be found as much or even more in the evolution of protective and corrective devices for telephone circuits as in the elimination of causes as attempted by these rules. It is quite possible that telephone circuits, being more sensitive, are now somewhat at the mercy of the less sensitive and more rugged power circuits and therefore should have some relief, but such a measure as this can but reverse the relation with far more hardship, while accomplishing nothing toward the final and equitable solution of the question.

A suitable code of rules, as scientific deductions reported to a scientific body or, accompanied by its natural counterpart in similar rules for the telephone industry, if adopted by this society, would be entirely proper and useful as a consensus of present opinion, subject to future advances. But these rules as law, inflexible to changing conditions and without such counterpart, are without equity or sense of proportion and contrary to economic order. Beyond the direct hardship imposed lies a greater wrong. Through their partisan point-of-view and narrow treatment of the issues, they establish by implication the principles of the power industry's legal liability for all possible effects of their circuits and of the telephone industry's fundamental right, wherever it may go, to an atmosphere free from magnetic influence, regardless of degree or priority of presence.

J. B. Fisken: I am sure a discussion of this paper, more especially of the rules, needs no apology before this body. I believe that rules or statutes should be discussed by engineering bodies when engineering is involved. Now, in anything I may say as to my opinions, I would simply state that I have been handling for a matter of twenty-eight years voltages varying from 90 to 60,000 and I have had quite a little experience. I want to refer to page 1446, under "definitions;" "a. Power Circuit," and "d. Line." These definitions provide for the inclusion in circuits which must be transposed, of arc circuits of voltages of 5,000 volts or more. But the rules do not state how they should be transposed. Series arc circuits are quite frequently run with one wire on a street; the return wire may be half a mile away. The people of California may have to string both sides of the circuit across this distance of a half mile to get a transposition, or build both sides of the circuit parallel to the telephone line.

I think there has been a mistake made in the arrangement of the rules; as, under Rule II, section "a," there is a rule which should be arranged under the heading of "Phantoms." A phantom, as I understand it, is something that has no apparent existence. As I regard this rule, and as Mr. Nunn has stated, it has nothing whatever to do with inductive interference; to my mind there is only one thing I can see it has to do with, and that is an imaginary physical hazard which does not exist.

A. H. Halloran: Since the earliest times an honest difference of opinion has always been an incentive to progress. Mr. Nunn evidently believes that this scientific investigation as to means for keeping a proper balance of power in circuits paralleling telephone lines, throws the balance of power too strongly in favor of the telephone company. Yet it should not be forgotten that the power companies have been the aggressors. Telephone circuits existed many years before there were power circuits. The telephone companies have spent thousands of dollars in vainly trying to solve the problem by compensating their own lines. Efforts were also made to adjust the matter legally, but

it was recognized that the subject is primarily an engineering problem. Consequently, while it may be admitted that the burden of correction is now laid upon the power companies, their representatives on the committee have recognized that it is only by the true spirit of co-operation that any mutual understanding can ever be reached. The report is admittedly only preliminary, and the committee stands ready to make any adjustments or corrections which may be found necessary.

A. J. Bowie: I have been greatly interested in the report of the Committee on inductive interference, particularly as this deals with a field of investigation about which little has been written prior to the present time. Insofar as the findings of the report are based on actual tests and data, it furnishes a very interesting study.

The letter of transmittal states: "Therefore the rules are not put forth as being final or complete but must be regarded as provisional and subject to such change as the results of further investigation and experience may determine."

However, experience with which the committee is apparently not familiar has already demonstrated that their recommendations on switches and switching are based on a very unsubstantial foundation. Quoting from the "Discussion of Rules," on Rule II, h, i, j:

> The commonly recognized fact that oil switches produce less severe transient disturbances in power circuits, affords the basis for the provisions in the rules dealing with switches and switching.

Quoting from the report itself, Section II, the following rules are laid down to govern switches:

> h—*Switch Equipment.* A power circuit involved in a parallel shall be equipped, between the source of supply and the parallel, with oil switches, all poles of which shall be mechanically interconnected for simultaneous action. With the exception of stations where an operator is constantly on duty, these switches shall be rendered automatic for short-circuits, grounds, and abnormal neutral currents.
>
> i—*Switching.* All switching on all parts of a system connected to a circuit involved in a parallel, which causes harmful transient disturbances in communication circuits, shall be done by means of oil switches, all poles of which are mechanically interconnected for simultaneous operation.
>
> j—*Use of Air Switches.* The use of air switches, on a power circuit involved in a parallel, is prohibited except for purposes of isolating sections of dead line, or for disconnecting transformers under no load. This applies to the entire power system, any circuit of which is involved in a parallel, unless such switching is so remote as not to cause harmful transient disturbances in the communication circuits.

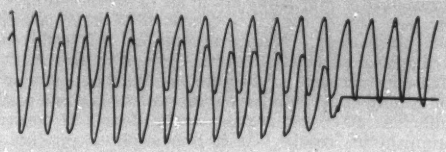
One of the important expenses in the transmission and distribution of power is the cost of high-tension switches. Air switches represent a very material saving to the consumer over the cost of oil switches, as their prices will range from about

one-third to two-thirds of the cost of the latter for switches of equal capacity. In addition thereto, air switches effect a still more important saving for high-tension work in that they may be located out-of-doors, whereas the housing of oil switches in many cases costs as much or more than the switch itself. Therefore the use of air-break switches will effect a material saving to the power companies and hence no rulings of any nature should be passed to forbid this saving unless the air-break switches produce an extremely bad and undesirable effect which will more than offset the great saving from the use of this type of switch. Hence it is with great astonishment that I note the report in this respect does not pretend to be based on scientific tests but on what is termed a "commonly recognized fact." At one time it was a commonly recognized fact that the world was flat and the universe revolved around it. It is unfortunately the case in engineering, as in other matters, that theories based on insufficient data obtain partial credence and are accepted without real investigation.

By the use of expensive and complicated apparatus it is possible to establish a very short arc in air in an exceedingly strong magnetic field and to make the arc so established set up high-frequency oscillations. But to accomplish this result requires the use of special apparatus entirely foreign to that used in any air switch construction. It is quite possible that an arc produced under oil might under similar circumstances become oscillatory when sufficient attention is paid to the details of construction to accomplish this result. As it is possible to produce an oscillatory effect in air many engineers without investigation have sincerely believed that the operation of air switches would cause a high-frequency surge, and this has resulted in a certain amount of prejudice against the use of air-break switches.

An interesting article has just appeared in the *General Electric Review* of September, 1914, by Mr. W. P. Hammond, Engineer of the Northern Contracting Company, giving a description of extensive tests on air-break and oil switches, conducted on systems of 44,000 and 110,000 volts, opening loads of several thousand kilovolt-amperes. These tests fully demonstrate the fact that in many respects the air switches are superior to oil switches. Quoting from the article: "In order to get a general check on the voltage surge, set up on the load side on opening the circuit with an air-break switch, a needle point spark gap was connected to two of the phases, set accurately for different voltages, and the maximum sparking gap noted for each switch under the same load conditions. The same experiment was tried on an oil-break switch in the circuit and the maximum sparking distance recorded when the circuit was opened with this switch was greater than with the air-break switch." This shows that oil switches cause a greater surge and rise of voltage than air switches. The article further states "The oscillograph records obtained during these tests do not indicate that there is

any high frequency set up on the lines by air switches which is especially dangerous to the equipment." Also, "The spark gap test previously referred to in this article would indicate that the surges in the voltage set-up by the air-break switch are not so violent as those set up by an oil switch, although this is not in line with the current opinion." Also, "The general conclusion drawn from these tests is that the air-break switch will doubtless replace the oil switches for many uses." Thus it is apparent that the air-break switches do not set up material oscillations in the circuit. The illustration herewith, from the above-mentioned article, is an oscillograph record showing the conditions when opening a 50,000-volt system and interrupting an energy load of 2500 kv-a. with an air-break switch. The upper curve represents the voltage on the supply system, and the lower curve represents the current. It is of particular interest to note that the current curve tapers off gradually, the time of tapering consuming about six cycles. This is a very important consideration in the action of air-break switches,



SHOWING INTERRUPTION OF AN ENERGY LOAD OF 2500 KV-A. WITH AN AIR-BREAK SWITCH

showing that the introduction of the high resistance of the long arc cuts down the current before the moment of final break, thus lessening the voltage rise over that which occurs with an oil switch, where the break is more sudden. The time of operation of air switches is in general from one to three seconds, provided the switch is not overloaded. The actual time will, of course, depend on the design of the switch, as well as on wind conditions. The time given above is a result of a long series of observations.

The conditions of opening of an air switch are commonly misunderstood. A short arc in an air switch will be of relatively little resistance so that until the arc lengthens materially, there will be no substantial change in the current conditions over those obtaining prior to the opening of the switch. After the arc has lengthened sufficiently, an effective gradual decrease in the current will occur and will require only a few cycles. Thus, for illustration, if it took the switch in question three seconds from the time of opening the switch until the arc was extinguished, this would last over a period of 180 cycles. During the

first 174 cycles, no very material change would take place in the conditions of operation over what existed prior to opening the switch. During the last six cycles, the resistance of the arc increases rapidly, thus gradually diminishing the current up to the point of final break. At worst, even if the switch operation does affect the telephone lines, the period of such operation is exceedingly brief, also, the switch operation is in general very infrequent on high-tension lines, so that even if severe disturbances should be produced, the total time during which the telephone service would be affected in a year would be so small as to be practically negligible in comparison to the saving to the companies and consequent saving in the cost of power delivered to the consumer.

From the foregoing the following conclusions are drawn:

1. Air-break switches will produce less rise of voltage than oil-break switches, and hence will not affect the telephone system as severely as the oil switches.

2. No material high-frequency surges are set up on the opening of air switches.

3. The duration of opening of air switches is somewhat longer than that of oil switches but the total time of such operation is so small as to be negligible in its effect on the telephone service.

4. The advantages of air switches are very much greater than any disadvantages cited.

I might add further that air-break switches are in use for controlling many important lines, among others, the longest line in the world, comprising the system of the Southern Sierras Power Company, which transmits power from Bishop to San Bernardino, a distance of 240 miles. Also, I have installed many air-break synchronizing high-tension circuit breakers for synchronizing high-tension lines, and according to all reports received the operation in synchronizing is perfect, and does not cause the slightest appreciable disturbances of the system.

I am sure that everyone will agree in the suggestion that before drastic rulings on switching are adopted by any commission, more complete investigations should be made as a basis, rather than the unsubstantial basis of "commonly recognized fact."

George S. Humphrey: Referring to the paragraph entitled "Minimum horizontal separation," I question whether the last three lines of that really mean very much. It says that crossings shall be "constructed in conformity with the National Electric Light Association's specifications for overhead crossings or other approved equivalent which may be agreed to by both companies." As most of you are probably aware, there was a resolution passed on this subject at the last meeting of the National Electric Light Association. This resolution reads as follows:

Whereas, at the annual convention of the National Electric Light Association in the year 1911 there was presented a report by the Com-

mittee on Overhead-Line Construction, to which the Executive Committee then gave its qualified approval, since which time the progress in the state of the art and the continued good work done by the Committee have developed recommendations of better practice which the overhead-line-construction committee now presents to this convention;

Therefore, be it RESOLVED, That the thanks of the Association are due and extended to the Overhead-Line Construction Committee for its sacrificing and painstaking efforts, and, in view of the later recommendations of that Committee, that the heretofore qualified approval of the 1911 report is hereby rescinded, and that the question of voltage limitation shall be eliminated from any recommendations or reports of any committee of this Association, by inference or otherwise, with relation to overhead-line construction practices, and that any such recommendations or specifications to this or previous conventions by any committee shall not be sanctioned by this Association.

This resolution was adopted by the National Electric Light Association in June, and so at the time these rules were prescribed by the Commission, there was not and is not now any such thing as "National Electric Light Association's Specifications for Overhead Crossings." No such specifications are included in the Handbook on Overhead-Line Construction, which was published at that time.

It appears that in defining telephone circuits, telephone systems of high-tension operating companies are included as a telephone circuit. The term includes any metallic telephone circuit operated by any railroad or other company for dispatching purposes. I just wondered if private telephone systems of transmission companies are included in that definition of the telephone circuit.

In the section of the country with which I am familiar there were formerly two telephone systems, and they have lately been consolidated. Now almost every important road in the country has a telephone line on each side of the road which is owned by the same company. I wonder what the recommendation of the Committee would be as to where the line of the power company should be placed along these roads.

J. C. Martin: I think Mr. Nunn has covered the practical aspects of the question about as well as it can be done. However, from the standpoint of the experience that I have had in connection with transmission and distribution problems in the Northwest, I have a few suggestions to make.

The 5000-volt limitation is particularly bad. The company that I am connected with operates a great many miles of 6600-volt circuit. So far as any records we have, or anything that we have heard from the telephone companies, show, we have no trouble due to inductive interference with properly constructed telephone lines. These rules would practically put us out of business as far as the 6600-volt line construction and operation is concerned. That is especially true because of the rule covering transformer connections. Owing to the conditions we have to

meet we make very frequent use of the open-delta connection and do not operate any of our single-phase transformers without grounding the secondary neutral.

On the question of telephone lines occupying both sides of the road: I think here in the Northwest, and I believe in most portions of the country as well as the Northwest, you will find that every country road has at least one telephone line that usually succeeds in occupying both sides of the road, and often there are two or more lines that stagger from one side of the road to the other. The lines are ordinarily ground return circuits and the construction adopted is usually the very cheapest that can possibly be used and have the lines stand at all, and no effort is made to even install the ordinary telephone protections. I am wondering, with Mr. Humphrey, what would happen in case a power company desires to build a line of over 5000 volts along such a country road, either in the State of California or wherever these roads might be located, and these rules enforced. The power company could undoubtedly be forced to rebuild such lines completely if these rules were in force. It seems to me absolutely unjust to force the power companies to stand the trouble that is due in many cases entirely to the poor construction of the telephone lines involved.

Like Mr. Nunn, it appears to me, from the wording of these rules, that a large number of important questions of design are left to the sanction and fiat of the telephone company; in other words, the engineers of the power companies are without any voice whatever in the matter as to how their service shall be handled or as to the methods or designs they shall adopt to best serve their customers. I know that in the territory we are serving the burden put upon the company in complying with rules of this sort would practically prohibit the serving of a large number of our customers and prospective customers.

Again, the telephone companies are relieved of practically all responsibility in the matter and the power companies are saddled with the responsibility and expense of avoiding any trouble that it may be necessary to take care of. I believe it will be conceded that the power companies furnish service that is as much of a public necessity as that furnished by the telephone companies. If any action is to be taken, the responsibility of caring for the trouble should be divided equally between the parties involved, and the telephone companies as a whole should be forced to a standard of construction that will be at least equal to that maintained by the power companies.

L. J. Corbett: Entirely apart from the legal aspect of this report, I think that we are fortunate in having it before us for its value as a technical contribution. It represents the investigations of a committee which was well equipped; it presents some of its findings, and contains certain recommendations which do indicate to us how we may avoid interference.

There is one thing that attracted my attention at first glance

at the paper, and that is in one or two of the definitions, the use of the term "residual." Possibly most of you would not take up such a point as this, but at first glance I wondered which meaning of "residual" was intended. I find that it refers to "the vector sum of the current in the several conductors of a power circuit." We are used to thinking of residual as something left over, a residual charge upon a condenser, residual magnetism in a field, and it seems to me we are using an old word for a new idea, which new idea requires a separate definition for the old word. It does not give us the idea at once as to what is meant, and I wonder if this committee gave any great thought to this matter in drawing up their definitions. It would seem that a word could be found which would connote the idea a little better than this word residual.

In reference to Mr. Fisken's question about the series circuit, I would offer as a suggestion that in such a case, according to this definition of residual, the entire current of the series system would be residual current and the entire voltage, the residual voltage.

Charles P. Kahler: In the discussion of Rule V the following comment is made:

> *V.* The Committee has undertaken no investigation of cases of parallelism with alternating-current railways, but as the seriousness of this class of exposure is recognized, it was thought desirable that it be referred to specifically.

However, although the Committee admits that it has made no investigation upon which to base any regulations for such conditions, nevertheless, it has undertaken to make such regulations, as shown by the following portion of Rule V.

> In the present state of the art, no means for completely overcoming inductive interference from such parallels is known, hence, they are to be avoided if possible.

If such rules were in force in the State of Washington, could the Inland Empire System be extended if there was a telephone or power line in the territory where it is proposed to extend it? It is well known that considerable study has been made to eliminate disturbances caused by both alternating- and direct-current railway circuits, and the latest work and information on this subject would indicate that trouble from this source may be overcome. The fact that the railroad companies themselves have to maintain communication circuits makes it necessary to provide means to prevent interference with them. It does not appear to me proper to add rules which may cause unnecessary expense to any electrification proposition unless the effect of such rules is definitely known.

L. T. Merwin: I was greatly pleased with Mr. Nunn's calm, judicial manner in opening the discussion and with the

nature of his remarks from the standpoint of a power man. Mr. Nunn, I think, has gone right to the quick of the matter from the standpoint of the power man, and "forewarned is forearmed." This thing has been done in California; most of you gentlemen are from northern states, northwestern states; if such a thing as this is to be put in a legal form in Oregon or Washington or Idaho or Montana I am sure there will be before the respective commissions of these states very well prepared and vigorous opposition, and rightly so, I believe.

I have great admiration for this paper as a scientific document; it puts before us in a very lucid way some things that we all wanted to know, but it puts them also firmly before us in a positive legal way, not bringing out what we may do, but, "Gentlemen, how do you like this? This is what you have to do." It is written by a body of men of undoubted scientific attainments and is presented to us as their findings, but presented as their findings after those findings have been put into legal form. It isn't here for our discussion as to the merits of the thing from an engineering standpoint, it comes as an absolutely closed book, and I feel very sorry for the power companies operating in California.

Mr. Humphrey brings up the point as to what will happen in a legal way, or how is one to interpret the situation, if the communication company is also the power company, considering its own communication lines. Mr. Nunn very clearly stated what could be done: The power company can simply sneak away from itself out of that "back door." That is all right and is easy.

We have a line of our own; I have been troubled with induction on that line for some seventeen months. On about fifty miles of our power line we had considerable difficulty owing to the topography of the country. It passes down along the north bank of the Columbia gorge. I have found it absolutely impossible, try as I may, up to the present time to neutralize the inductive effects on the telephone line. The power line is not transposed. However, we have done something else than transposing, and it seems to me that the telephone company might do the same. I have simply given up all efforts to get rid of induction, I have accepted it as a fact, and then looked around to see if I could kill it or get rid of it insofar as the receiver of the telephone instrument was concerned, and I believe that I have succeeded. Now if a power company can succeed surely the minor disturbances that arise on the telephone lines can be taken care of by the telephone companies. It seems that those slight residual effects—I mean residual not in the sense in the paper—can still be neutralized. Very briefly, and as an aid to others who are having the same trouble, I have learned through the manager of the Federal Wireless Telephone Company in Portland of a high-power transmitting instrument made by some private firm in Seattle, the name of which I shall be glad to give to any

one. I have arranged reactors and condensers into a resonant circuit at the instrument, and found I could actually neutralize the inductive effects of the power line at the instrument. With an ordinary transmitter the working current is not strong enough to force through the series impedance of this arrangement. By using this high-power telephone transmitter I found I could get sufficient amplitude of talking current. I simply mention this as a possible relief to other power men who have had the same trouble with their own telephone lines.

C. E. Rogers (by letter): This report is very interesting as it covers a subject to which much space in the scientific press has been devoted in a qualitative manner, but, like previous papers, it does not give any quantitative results. I realize that many more formulas are yet to be derived in order to present this subject with mathematical accuracy, such as has been done in the calculation of corona losses, and I regret that at least one appendix has not been devoted to the calculation of the voltage and current induced in the communication circuits of one of the exposures mentioned. In order to present the rules that have been recommended, these data must have been accumulated, and an appendix containing quantitative information would receive deserved attention and valuable criticism.

A. J. Bowie, Jr. (by letter): Supplementing my oral discussion of the report of the inductive interference committee, the most direct and authoritative evidence on results of opening air switches can naturally be obtained from companies making extensive use of apparatus of this nature. Consequently for further investigation of this subject, I have written to The Pacific Power Company, Bodie, California, and The Southern Sierras Power Company, Riverside, California, both of which companies employ air switches, almost exclusively, for their high-tension systems.

I have addressed the following questions to these companies:

(1) Have you on your lines any material length of what may be termed parallel to the communication circuits?

(2) To what company do the communication circuits belong?

(3) Has your company ever received complaints from owners of communication circuits about the inductive effect of your power lines?

(4) Have any specific complaints ever been received of trouble in communication circuits from switch operation?

(5) If so, what is the general nature of such complaints, *i.e.*, as affecting the interference with communication or as affecting any safety or any other apparatus connected to their system?

In reply thereto, I have received the following answer from Mr. C. O. Poole, Chief Engineer, Southern Sierras Power Company:

(1) We have several cases that might be used under the term parallel to the communication circuits.

(2) The communication circuits belong to The Pacific Telephone &

Telegraph Co., the Southwestern Telegraph Co. and The Western Union Telegraph Company.

(3) We have received several complaints from the Pacific Telephone & Telegraph Co., Southwestern Telegraph Co., and the Interstate Telegraph Co., of the inductive interference with their communication circuits.

(4) We have not received any specific complaints of disturbances caused by the operation of air switches. We have, however, received complaint from the disturbances of the service caused by the charging of the electrolytic lightning arresters. We are preparing to install current-limiting resistors which will probably reduce the cause for complaint.

Reply from Mr. W. N. Chatfield, General Manager, The Pacific Power Company:

(1) Telephone lines parallel our transmission line for a distance of 125 miles, and are on the same poles as the transmission line for a distance of 66 miles.

(2) Telephone lines used in connection with power operation and not for public use.

(3) We have received no complaints on account of inductive effects on the telephone lines. Naturally there is a good deal of induction on the telephone line but not so that it interferes in any way with the operation of same, and as the line is for our own use, naturally no one has any complaint to make.

(4-5) We have not had any trouble to amount to anything in our telephone system caused by switch operation on the transmission line.

It is greatly to be regretted in making this investigation, that the committee did not avail itself of the experiences of some of the largest users of air switches on the Pacific Coast. Had it done so, I feel sure its report on this subject would have taken a very different aspect.

All the evidence available, shows very strongly that oil switches will produce more severe disturbances than air switches on their own, as well as on neighboring lines. There is one feature of the report which is most inconsistent, namely, the prohibition of air switches, and at the same time the allowance of the use of electrolytic lightning arresters. From the very nature of the electrolytic arrester, the breaking of the current either when the arrester is being charged, or when the arrester is operating, is very abrupt, and hence very apt to cause undesirable effects on parallel lines. To be at all consistent, the electrolytic arrester should have been included in the general prohibition of the subject of arcs in air.

Even though oil switches will cause more severe disturbances than air switches, there is certainly no reason sufficiently strong, at the present time, to render advisable in any way the prohibition of any special type of switch, and legislation in this direction is a definite step backwards.

Joint Committee on Inductive Interference: The above discussion of the report of this Committee discloses many

misunderstandings, some of the clear meaning of the recommendations, but mainly of the scope and the spirit of the Committee's work. This scope and spirit may perhaps be best expressed in words as follows:

The State of California must have both electric power and electric communication. The former now conflicts with the latter and the conflict is becoming more serious year by year as the two services expand. When the two services approach their ultimate development of universal power distribution on the one hand and universal communication on the other hand, the conflict will greatly hamper the communication service if the power service is permitted to expand with no limitation of its inductive effects. The greatest good to the greatest number, which is in this case the best and cheapest power service combined with the best and cheapest telephone service to the people of the State, will be obtained by the imposition of such burdens on the power service as will result in improvements to the telephone service greater than the burdens imposed. The Committee contends that each of the burdens imposed on the power service by the rules recommended will result in an improvement of the telephone service to the citizens of the commonwealth totally out of proportion to the interference of those same rules with power service to the citizens of the commonwealth. This view has been kept clearly in mind in the formulation of each ruling recommended to the State Railroad Commission.

The Committee admits that "benefits accrue only to one interest while burdens are laid upon the other." Since by no stretch of the imagination can the inductive effects of communication circuits as now operated (wireless excepted) be considered as interfering with power circuits, the latter will not be benefited. No engineer should intimate that such a benefit should be sought. The Committee does not admit, however, that the burdens are "extreme hardships," but contends that these burdens will in all cases do more good than harm to the public services of the State as a whole.

Admittedly, "the Commission is led to adjudicate the differences and legislate changes in practise from scientific considerations alone * * * *" and all praise is due the Commission for this action. But the Committee submits that there the "broader aspects of the issues involved," viz., equity, inherent rights, the evolution of the respective industries, and the policy of the public toward its utilities, are all covered by or are subordinate to the principle of the greatest good to the greatest number. This has been the chief consideration followed throughout.

The Committee does not agree that the rules "establish by implication the principle of the power industry's legal liability for all possible effects of their circuits," but does contend that they establish in California the power industry's legal liability for unnecessary, unwarranted or avoidable inductive effects

where such effects will work hardships materially greater than those necessary to avoid them. Neither do the rules establish "the telephone industry's fundamental right, wherever it may go, to an atmosphere free from magnetic influence, regardless of degree or priority of presence." They do establish the telephone industry's fundamental right, wherever it may have metallic interexchange circuits (not subscribers' circuits), to an atmosphere free from inductive influences so great as to cause harm more serious than the burdens imposed on the power industry by reducing such influence.

The Committee admits the justice of the criticism (favorable or unfavorable) that "the scope of the restrictions placed upon power interests is without tangible limit." The absolute impossibility of determining in the general case, for example, to just what extent the residual current in a power circuit can be reduced with a burden on the power system less than the benefit to the telephone system, makes it necessary to use the expressions criticised, "closely as practicable", "every reasonable effort", "low as consistent with good practise," etc.; unfortunately, perhaps, the communication interest is the party best able to judge the effects of these intangible quantities and this interest has been given in some cases the right within fixed limits to specify quantities, on the assumption of co-operation, with the Commission as a court in case of disagreement. The Committee hopes that its future work will make it possible to be more explicit with respect to such quantities as are capable of quantitative analysis into burdens and benefits.

The Committee admits also that the communication interests have much of their future life to gain and nothing to lose by the investigation and its results, and that the power interests have nothing to gain and little to lose as compared to the gains of the other party; for which reason the telephone interests have contributed to the work more men, funds and equipment than have the power interests, and have naturally taken a deeper interest in the work. Admittedly also, the telephone interests of practically the whole country have been pitted against the power interests of California, which in this work were not "competitive and without cooperative organization." But the Committee denies that the natural zeal set up by this greater incentive has been effective in making its recommendations depart from the principle of the greatest good to the greatest number.

A more nearly just criticism is that "the problem lies no more with the cause and its removal than with effects and their prevention," but the Committee has not yet found many opportunities for improvement of telephone plant or operation because the telephone interests have already made many such improvements.

It is not true that "none of the expense or burden of this new regime falls upon the telephone interest." The rules recom-

mended cover retransposition of the telephone lines to match power line transpositions, which is no small requirement, since many telephone transposition points are required for each power transposition, and with a heavy telephone lead there must be a large number of transpositions at each transposition point. It is hoped that the future work of the Committee may develop other possibilities of improvement of the telephone plant.

The more specific criticisms of details of the report are subject to the following comments:

The requirement of wave shape of synchronous machinery does not mean that the power companies of California are now using generators of inferior characteristics, nor does it mean that "electrical manufacturers must now evolve a line of generators of new design and characteristics for the special needs of California trade." It does mean that due weight should in the future be given the matter of wave form from the standpoint of its possible inductive effect on other circuits. There is nothing extreme contemplated. The Standardization Rules of the Institute are set up as the limiting requirements.

With regard to the exciting current of transformers, investigation will show that the 10 per cent limitation covers all ordinary practise and good design, but excludes densities so excessive that they might be considered "freaks."

The requirement of oil switches rendered automatic for abnormal neutral currents, far from being beyond mechanical possibility, calls only for the addition of the most simple kind of an overload trip connected in a circuit of ground potential.

The rule regarding line testing in case of trouble does not "prohibit present prevailing practise" as far as California is concerned, and does not "require the development of new methods and new apparatus for the localization of line faults," but does enforce the best prevailing California practise, without new methods or apparatus.

The record of hourly measurements of neutral currents is called for only at the main generating and substations, at most, if not all of which, operators are on duty at all times, for which reason this rule does not "in effect seem to require a regular corps of attendants at every point of transformation employing a ground connection."

Harmonics of either voltage or current in a power system, far from being "a problem of many years study by engineers, manufacturers and power companies alike,, the solution of which might have saved from financial failure many of the power ventures of the past decade," are usually inappreciable so far as the operation of the power system itself is concerned, and in the few extreme cases where they are so appreciable, they can be reduced without material expense.

The only rule affecting construction at points of close proximity is not outside the scope of the Committee's work, as an examination of that part of the report covering the formation

of this committee would show that the Railroad Commission called for recommendations "tending to minimize inductive interference *and physical hazard* arising from parallelism of different classes of circuits."

The specifications referred to as those of the N. E. L. A. are well known in California as those embodied in the joint report of the Committee on overhead line construction of the N. E. L. A., the High-Tension Transmission Committee of the A. I. E. E., the committee on power distribution of the A. E. R. A., and other committees, and were referred to by the above abbreviated name since the same name is used by the Railroad Commission of the State of California in its General Order No. 26 covering overhead crossings.

Series arc circuits are not constant potential in character and are therefore excluded from the rules under the definition of power circuits.

The criticism referring to roads with telephone lines on both sides is generally inapplicable, as most such duplication is of subscribers' circuits, which are excluded.

Some other criticism might be similarly shown to be due to a lack of care in reading the report or of familiarity with the subject.

The criticism of the ruling on the use of air switches has been based on an entire misinterpretation of the spirit of the work. The Committee stated that the reason for this ruling was the commonly recognized fact that oil switches produce less severe transient disturbances in power circuits. While this may not be true so far as voltage rise in the power circuits is concerned, the disturbances which affect by induction neighboring communication circuits are far more severe when air switches are used than when oil switches are used. The disturbance of a power circuit due to switching that causes the greatest inductive interference is the breaking of one or two phases in advance of the other two or one phase. In case of a system with neutral grounds this action gives a large momentary ground return current in the power circuit. In case of an isolated system this action gives momentary application of full line voltage to only one or two conductors, with no balancing voltage on the other conductor or conductors. Either result causes inductive effects excessive as compared with normal operation. A properly constructed oil switch gives more nearly simultaneous interruptions in all poles, hence this inductive effect is of shorter duration. The published data on which this ruling has been criticised give the following information on this point:

The maximum time necessary in which to interrupt the arc in any of the 50,000-volt tests was 25 seconds and the minimum 2 seconds, the average time for a large number of the tests being 6 seconds. The average time necessary to interrupt the arcs in the 110,000-volt test was 7 seconds, the maximum being 16 and the minimum 3. This means that the air-break switch requires anywhere from 120 to 1500 cycles in which to interrupt a circuit, while the oil switch may accomplish this result in half a cycle. (*General Electric Review*, Sept. 1914, page 868).

Other tests on oil switches show breaking of all three phases within a small fraction of a cycle. With air switching requireing several hundred cycles to break the circuit, the instant of breaking of each phase depends upon atmospheric conditions, and the three breaks are separated by far longer time intervals than those of oil switches. The excessive residual currents and voltages during these time intervals give inductive effects commonly described by the telephone colloquialism "a bat in the ear." The Committee has records of many cases of temporary injury to hearing, both from air switching, and from the use of oil switches not properly interconnected for simultaneous action. Members of the Committee represent by far the largest users of both air and oil switches on the Pacific Coast and also represent interests having by far the largest number of parallels existing in California, if not in the world. The experience of the interests represented amply confirms the scientific bases for these rulings.

A. H. Babcock (by letter): If the minutes of the meeting at which the Joint Committee was organized could have been published with the report, certain criticisms, perhaps, would have been worded differently. The minutes are too lengthy for publication, even in abstract, but the history of the organization of the committee as recorded therein is now given to show the reasons for the investigation, the spirit in which it was undertaken and prosecuted, and the representative character of the members of the committee.

Several complaints had been made to the Railroad Commission by the Pacific Telephone & Telegraph Company, against inductive interferences by certain power companies' circuits. Tests to determine causes and remedies had been carried on for two months by the companies involved, working with the authority of the Railroad Commission Engineering Department. The results promised so much that, at the request of the chief engineer of the Railroad Commission, a general meeting was called "between representatives of various telephone, telegraph and power companies of California, and representatives of the Railroad Commission of the State of California, for the purpose of appointing a committee to conduct tests and gather information with reference to induction matters, both applying to cases now before the commission, and generally throughout the State." (Minutes).

Invitations to appear at the meeting were sent to every telephone, telegraph and power company operating within the State. Twenty-three companies responded by representative appearances. After a preliminary discussion the Railroad Commission requested all the power men to meet in one room, all the telephone and telegraph men to meet in another room, the two groups each to name four men to serve on the committee, (subject to the approval of the commission), with four members of its engineering department staff, and one from the

railway interests, not included with either of the two groups in adverse interest, because the railways operate both power and communication circuits.

The president of the Railroad Commission in opening the meeting above mentioned said, "It is distinctly understood on behalf of the commission that we desire to have this committee appointed representing the power companies and the telephone and telegraph companies and this commission, and that of course the recommendations of this committee will be very persuasive on the commission, but * * * * the commission will formulate the rules we * * * * believe we can get permanent results that will help us in the future on these matters of construction, and we desire it understood specifically that it is to be carried on not exactly under the direction but under the supervision of the commission with a view of a recommendation to this commission."

The personnel of the committee selected is given below.

Representing Railroad Commission:

Mr. R. A. Thompson, Chief Engineer.
Mr. A. R. Kelley, Assistant Engineer.
Mr. James T. Shaw, Assistant Rate Expert.
Mr. R. Emerson Hoar, Assistant Rate Expert.

Representing Railroad Interests:

Mr. A. H. Babcock, Consulting Electrical Engineer, Southern Pacific Company.

Representing Telephone and Telegraph Interests:

Mr. A. H. Griswold, Plant Engineer, The Pacific Telephone and Telegraph Company.
Mr. R. W. Gray, Division Superintendent, Western Union Telegraph Company.
Mr. C. H. Temple, General Manager, United States Long Distance Telephone Company.
Mr. L. M. Ellis, General Manager, Union Home Telephone Company.

Representing Power Interests:

Mr. H. A. Barre, Electrical Engineer, Pacific Light and Power Corporation.
Mr. Louis Elliott, Engineer, Great Western Power Company.
Mr. P. M. Downing, Engineer, Pacific Gas and Electric Company.
Mr. J. E. Woodbridge, Chief Engineer, Sierra and San Francisco Power Company.

The organization and personnel of the Joint Committee on Inductive Interference were approved by the Railroad Commission on January 6, 1913, and the committee thereupon proceeded with the necessary tests and investigations.

Since the formation of the committee, through additions, resignation or death, the personnel of the committee has changed as follows:

Mr. Louis Elliott resigned and Mr. J. A. Koontz, Engineer of the Great Western Power Company, was appointed in his place.

Mr. V. V. Stevenson, Electrical Engineer of the Postal Telegraph Cable Company, and Mr. L. N. Peart, General Superintendent of the San Joaquin Light and Power Company, were added to the original membership by action of the committee.

Mr. R. A. Thompson, Chairman of the Joint Committee, resigned. Mr. W. C. Earle, his successor as Chief Engineer of the Commission, was elected to membership and chairmanship. Subsequently Mr. Earle resigned and Mr. Richard Sachse, then Acting Chief Engineer, now Chief Engineer of the Railroad Commission, was elected to membership and chairmanship.

Mr. L. M. Ellis resigned and Mr. R. W. Mastick, Transmission and Protection Engineer of The Pacific Telephone and Telegraph Company, was elected to membership.

Mr. H. S. Warren, Electrical Engineer of the American Telephone and Telegraph Company, was elected to honorary membership.

Mr. James T. Shaw, Secretary of the Joint Committee, resigned. Mr. A. R. Kelley was elected to the office of secretary. The vacancy in membership created by the resignation of Mr. Shaw was later filled by the election of Mr. A. L. Wilson, Assistant Rate Expert of the Railroad Commission. Mr. James T. Shaw was elected to honorary membership.

The death of Mr. L. N. Peart created a vacancy in membership which was filled by the election of Mr. J. P. Jollyman, Engineer of Electrical Construction of the Pacific Gas and Electric Company.

Mr. A. R. Kelley resigned and the vacancy was filled by Mr. A. F. Bridge, Assistant Electrical Engineer of the Railroad Commission.

The Chief Engineer of the Railroad Commission always has been Chairman of the Committee.

The power companies whose officers are named above are the ranking companies of this State, in respect to age, extent of system, and magnitude of interests involved. In at least these respects they may be compared with any other similar interests elsewhere. Their representatives have carried out the investigation in a spirit of non-partisan scientific search for the facts, and for the remedy of a condition, in a fashion that repeatedly has aroused the whole-hearted admiration of the other members of the committee.

The report represents the best efforts of those who signed it. Every sentence was studied carefully. Not one was passed for final copy until every member had been given full opportunity to present his views, and often, the final vote was not polled until certain members were satisfied that every man present understood the full effect of the vote on both sides of the question. In every case the vote was unanimous.

Presented at the 299th meeting of the American Institute of Electrical Engineers, New York, October 9, 1914.

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PROTECTIVE REACTORS FOR FEEDER CIRCUITS OF LARGE CITY POWER SYSTEMS

BY JAMES LYMAN, LESLIE L. PERRY, AND A. M. ROSSMAN

ABSTRACT OF PAPER

This paper outlines the use and limitations of protective reactance coils in feeder circuits. When no feeder reactors are used, doubling up the station capacity increases the number and severity of short circuits. The insertion of feeder reactors cuts down the severity of a short circuit and practically renders the effect local, so that beyond a certain point additional generator capacity does not appreciably increase the severity.

Curves are given showing what the effects of feeder reactors are, with and without bus reactors, for generators of various reactances. The advantages that might be gained by parallel operation of feeders are discussed and the difficulties to be encountered are pointed out.

INTRODUCTION

IN a paper entitled "Protective Reactance in Large Power Stations" presented at the 1914 midwinter convention of the Institute, the authors discussed the use and limitations of current limiting reactors in generator circuits and in power station busbars.

It was shown in that paper* that, on a radial feeder system, the use of busbar reactors tends to confine the disturbances from a short-circuited feeder to that section of the busbars to which the feeder is connected. It was also shown, in one example, that the use of 3 per cent feeder reactors reduced the amount of current flow into a feeder short circuit to 1/4 of what it would be without feeder reactors.

It is the purpose of this paper to discuss, in greater detail, the use and limitations of reactors in the feeder circuits of large city power stations.

The methods of deriving the curves of this paper are the same as are given in the appendix to our earlier paper. Where reference is made to maximum values this refers to maximum r.m.s. values and not to maximum instantaneous values.

*See Part I, this volume, p. 23.

Transient effects are not taken into account by these curves. The transient effects can be derived from the r. m. s. values.

The Need of Feeder Reactances

Consider the case of a 225,000-kv-a. power station which generates electricity at 11,000 volts. Such a station would have, say, 80 feeders each rated at 5000 kv-a. If these feeders average three miles in length there would be a total of 240 miles of feeder cable installed. If on this system there are five breakdowns per 100 miles per year, then there might be expected a total of 12 breakdowns per year on the system, or an average of one breakdown per month.

If the station capacity and the number of feeders are increased 50 per cent and the average length of feeder increased 331/3 per cent, then the breakdowns will average two per month. If all of the feeder cables are tied directly to the power station busbars and no reactors are used in either feeders or busbars, heavy short circuits occurring within a mile or so of the power stations would be felt over the entire system, and might be felt with troublesome severity even when occurring at greater distances from the power station. At times of light load, few machines are running and the portion of the short-circuit kilovolt-amperes carried by each machine on the system might easily be several times the normal load rating of each machine. Evidently one or two such general disturbances per month could not be tolerated. Properly designed feeder reactors limit the amount of short-circuit current in a feeder to such an extent that the effect is local.

Curves

In order to study the effects of different values of feeder reactance several curves have been plotted.

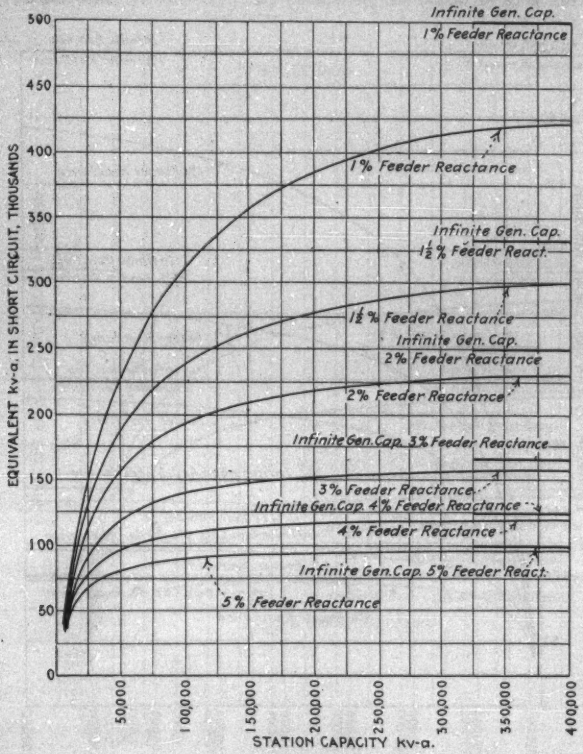
Curve Sheet 1 shows the relation between the equivalent kilovolt-amperes in a short circuit and the station capacity in kilovolt-amperes for six different values of feeder reactance when no bus reactance is used. The generators in this case have 12 per cent inherent reactance.

Curve Sheets 2 and 3 show similar sets of curves which differ from the curves on Curve Sheet 1 only in the values of inherent generator reactance, which are chosen at 10 per cent and 8 per cent respectively.

The points of special interest shown by these curves are:

(a) With infinite generator capacity the equivalent kilovolt-

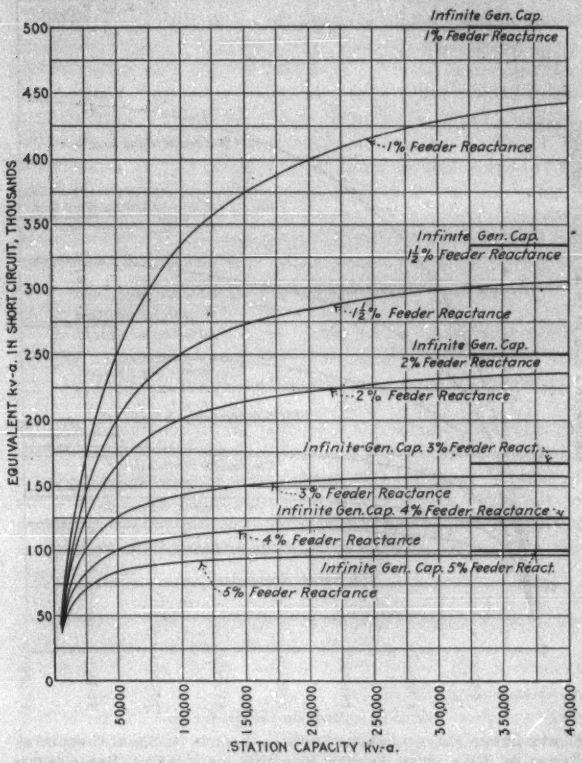
amperes in a short circuit vary inversely as the reactance in the feeder circuit.



CURVE SHEET NO. 1—CURVES SHOWING VALUES OF SHORT CIRCUITS IN TERMS OF KV-A. WITH FEEDER REACTORS OF VARIOUS PER CENTS—INHERENT GENERATOR REACTANCE 12 PER CENT WITHOUT BUS REACTORS—5000-KV-A. FEEDERS.

(b) The equivalent kilovolt-amperes in a short circuit with infinite generator capacity are the same for the three sheets of curves.

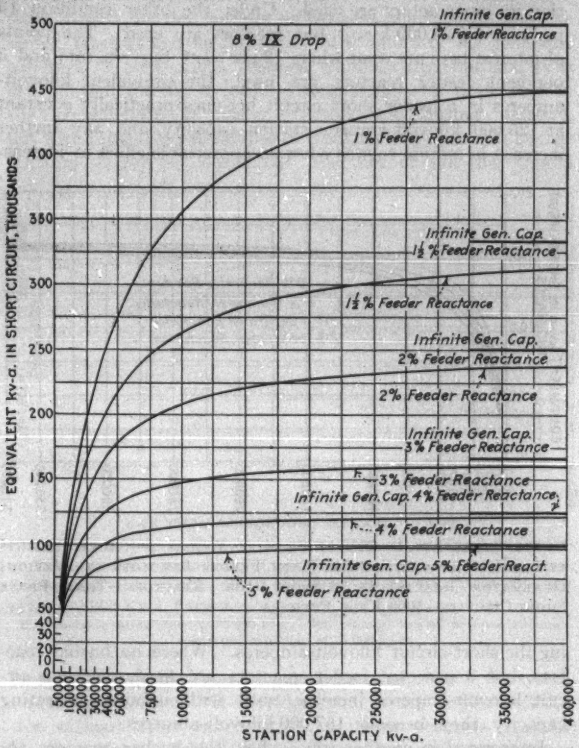
(c) The kilovolt-amperes in short circuit increase more rapidly per kilovolt-ampere of station capacity for a small station than for a large one.



CURVE SHEET NO. 2—CURVES SHOWING VALUES OF SHORT CIRCUITS IN TERMS OF KV-A. WITH FEEDER REACTORS OF VARIOUS PER CENTS—INHERENT GENERATOR REACTANCE 10 PER CENT WITHOUT BUS REACTORS—5000-KV-A. FEEDERS.

A comparison of similar curves on the three sheets shows that the variation in generator reactance does not greatly affect the curves. Curve Sheet 4 shows the four curves for 3 per cent (of

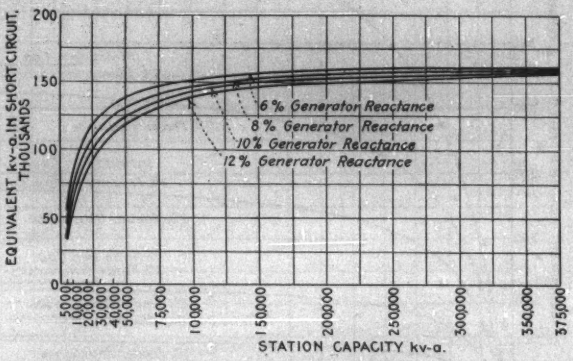
5000 kv-a.) feeder reactance replotted on the same sheet for generator reactance of 12 per cent, 10 per cent, 8 per cent and 6 per cent, respectively. By comparing the curve for 6 per cent



CURVE SHEET NO. 3—CURVES SHOWING VALUES OF SHORT CIRCUITS IN TERMS OF KV-A. WITH FEEDER REACTORS OF VARIOUS PER CENTS—INHERENT GENERATOR REACTANCE 8 PER CENT WITHOUT BUS REACTORS; 5000-KV-A. FEEDERS.

generator reactance with that for 12 per cent generator reactance the small effect of the generator reactance on the curves is evident.

Curve Sheet 5 shows the relation between equivalent kilovolt-amperes in a short circuit and station capacity in kilovolt-amperes with 10 per cent generator reactance and 3 per cent (of 5000 kv-a.) feeder reactors, under two conditions. Under one condition no bus reactors are used. Under the other condition 12 per cent (of 25,000 kv-a.) bus reactors are used. The points of interest here are, that where 12 per cent bus reactors and 3 per cent feeder reactors are used, the equivalent kilovolt-amperes in a feeder short circuit becomes practically constant at 125,000 kilovolt-amperes station capacity, and any further increase in station capacity has no appreciable effect in increas-

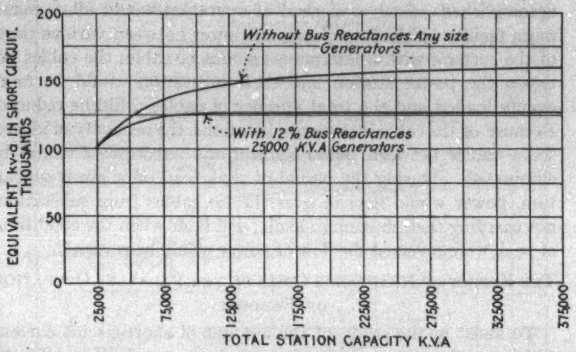


CURVE SHEET NO. 4—CURVES SHOWING VALUES OF SHORT CIRCUITS IN TERMS OF KV-A. WITH 3 PER CENT FEEDER REACTORS AND VARIOUS GENERATOR REACTANCES WITHOUT BUS REACTORS—THREE-PHASE SHORT CIRCUITS—5000-KV-A. FEEDERS.

ing the short-circuit kilovolt-amperes. Where no busbar reactors, but 3 per cent feeder reactors are used, the short-circuit kilovolt-amperes increase until with infinite generating capacity they become 167,000 kilovolt-amperes.

Interpreted in another way, when the busbar reactors are used, the feeder reactors absorb 75 per cent of the voltage and therefore give a 25 per cent drop in voltage on the section of the busbars to which the feeder is connected, under the worst conditions of short circuit. This means that all of the feeders connected to that section will suffer a momentary drop in voltage of 25 per cent. Where no busbar reactors are used, the feeder reactor

on the defective feeder will, under the worst conditions, absorb 100 per cent of the voltage and will pass 40,000 more kilovolt-amperes, but the voltage of the other feeders on the system will not be appreciably affected. If there were no possibility of a short circuit on the busbars or between the busbars and the feeder reactors and no possibility of a failure of the generator windings or connections between windings and busbars, it is evident that the use of feeder reactors alone is preferable to the combination of feeder reactors and busbar reactors, but with these live possibilities of trouble always present, busbar reactors should be considered. Whether or not they should



CURVE SHEET NO. 5—CURVES SHOWING VALUES OF SHORT CIRCUITS IN TERMS OF KV-A. WITH 3 PER CENT FEEDER REACTORS, 10 PER CENT GENERATOR REACTANCE—WITH AND WITHOUT 12 PER CENT BUS REACTORS—5000-KV-A. FEEDERS.

Bus reactance rating based on 25,000 kv-a. Bus reactors located between adjacent generating capacities of 25,000 kv-a.

be adopted depends upon the particular conditions of the system under consideration. It is evident that a very large power station without either bus reactors or feeder reactors is liable to short circuits which will endanger apparatus and service, due to the practically unlimited concentration of power in the short circuits.

EFFECT OF FEEDER REACTORS ON VOLTAGE REGULATION

At 0.8 power factor a 3 per cent feeder reactor will cause a voltage drop of approximately 1.8 per cent, at 0.9 power factor, a drop of approximately 1.3 per cent, at 0.95 power factor a

drop of approximately 1.0 per cent, and at 0.98 power factor a drop of approximately 0.6 per cent.

In large city power stations such as have been considered, there is always a considerable amount of synchronous apparatus in operation at a high power factor and the voltage drop due to 3 per cent reactance in their feeders will be low.

The Parallel Operation of Feeders

The paralleling of a-c. feeders on a set of busbars at the substation end and the tying together of the different substation buses by means of tie feeders between substations would be highly desirable on most of our large city systems, if it could be safely accomplished. Such a method of operation would allow maximum facility in the interchange of power between various parts of the system, with a minimum amount of cable; the cables between the power station and each substation would be more evenly loaded and the total number of cables could be reduced. Because of the cables between substations, the necessity of idle reserve cables between power station and substations would be eliminated. During the period of peak load on a given substation, power would flow in over the tie cables from substations not carrying their maximum loads; and later when the conditions of peak were reversed the flow of power would be reversed.

The Effect of Reactance Coils on the Parallel Operation of Feeders

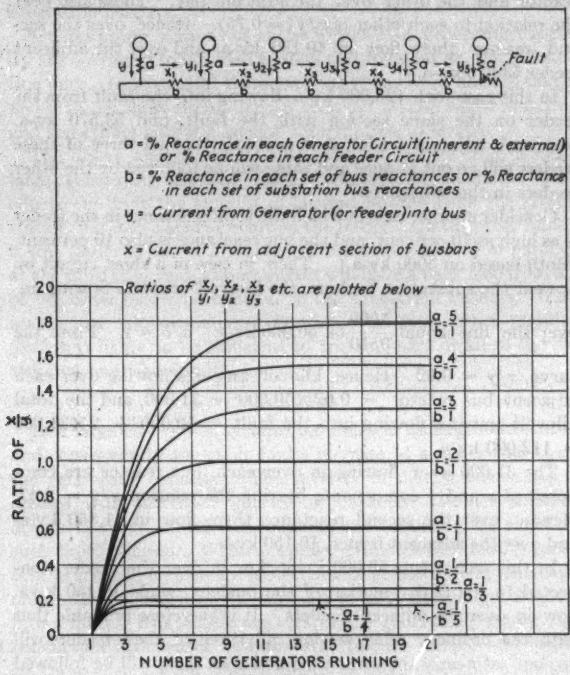
To assist in the study of the amount of short-circuit current which can flow into a fault, the series of curves on Curve Sheet 6 was plotted. These curves can be applied to approximate the amount of short-circuit current into a fault on the busbars of a power station where busbar reactors are used, or to approximate the amount of short-circuit current into a fault on or near the substation busbars where several feeder cables are connected in parallel on the substation busbars with busbar reactors between them.

As applied to the case of a power station, one or two examples will be cited. Assume the case where the ratio of generator reactance to busbar reactance (a/b) equals 1/3. The corresponding curve is almost constant with three running generators. This means a short circuit on any section of the busbars is practically maximum when the generator on the same section and one generator on each adjacent section are in operation, and the addition of more generators to the system will not appreciably increase the amount of short-circuit current.

Where the busbar reactance and generator reactance are equal ($a/b = 1/1$) the maximum value of current is nearly reached with five generators running.

In applying the curves to a substation, consider the following concrete example:

Consider a case in which the inherent reactance in each feeder



CURVE SHEET NO. 6

equals 1 per cent, artificial reactance equals 3 per cent, and bus reactance equals 3 per cent, all based on 5000 kilovolt-amperes. Then if a short circuit occurs on or near the substation busbars the kilovolt-amperes flowing in over the short-circuited line equal $\frac{5000}{0.04}$, or 125,000 kv-a. $a/b = 4/3 = 1.33$. From curves, by

interpolation, $x/y = 0.75$. Hence, the kilovolt-amperes flowing over each adjacent bus reactor equal $0.75 \times 125{,}000 = 93{,}750$ kv-a. and the total kilovolt-amperes flowing into the fault $= 125{,}000$ kv-a. $+ 2 \times 93{,}750$ kv-a. $= 312{,}500$ kv-a.

The 93,750 kv-a. flowing in over each bus reactor are composed of two components, one flowing in over the second reactor and the other over the adjacent line. These also bear the relation to each other of x/y $(= 0.75)$. Hence, over the second reactor there flow in 40,180 kv-a. and over the adjacent feeder 53,570 kv-a.

In this case with 125,000 kv-a. flowing into the fault from the feeder on the same section with the fault, and 53,570 kv-a. over each adjacent feeder, it is probable that all three of these feeders will go out at once and these will be followed by the other feeders in the substation.

Consider another case in which the total reactance in the feeder is as high as 10 per cent, and the bus reactance is also 10 per cent. (Both based on 5000 kv-a.). Then, in case of a short circuit on or near the substation busbars, the kilovolt-amperes flowing in over the line equal $\frac{5000}{0.10}$ or 50,000 kv-a. $a/b = 1$. From the curve, $x/y = 0.62$. Hence, kilovolt-amperes flowing over each adjacent bus reactor $= 0.62 \times 50{,}000 = 31{,}000$, and the total kilovolt-amperes flowing into the fault $= 50{,}000 + 2 \times 31{,}000 = 112{,}000$ kv-a.

The 31,000 kv-a. flowing in over each bus reactor are composed of x and y components bearing the relation $x/y = 0.62$. Hence, over the second reactance there flow in 11,850 kv-a. and over the adjacent feeder, 19,150 kv-a.

In this second case 50,000 kv-a. flow in over the feeder connected to the faulty section of the busbars, while 19,150 kv-a. flow in over the adjacent feeders. It is therefore probable that with the ordinary relay setting, all three of these feeders will go out at nearly the same time and that these will be followed by others. Furthermore, such large reactors in feeders and substation busbars would have a serious effect on the voltage regulation of the system, and would in a large measure defeat the purpose of their installation, viz., to permit the free interchange of power between different parts of the system.

Another arrangement of feeder reactors would be to place reactors at both ends of the feeders and omit the reactors

from the substation busbars. This scheme would be more objectionable than the one discussed above, because a short circuit on the substation busbars would be fed by the several feeders in parallel, and, if these feeder circuits were all alike, the kilovolt-amperes flowing into such a short circuit would be directly proportional to the number of feeders connected to the substation busbars.

Several power stations of about 50,000-kv-a. generating capacity are operating today with feeders tied together at the substation end. In several of these stations it has been noticed that a severe feeder short circuit usually trips out several feeder switches and sometimes causes a general interruption to service.

The above analyses show that even on feeders from a very large generating station, feeder reactors of moderate size effectively limit the amount of current flowing from the power station end into a short circuit on the feeder. On the other hand, if this feeder is one of a number of feeders connected in parallel at the substation end, a short circuit will have a back feed from all of the other feeders connected to the substation busbars. The amount of kilovolt-amperes flowing over these other parallel feeders is likely to be sufficient to trip out part or all of the oil switches on these circuits.

Summary

In a large city power system, the miles of underground cable and consequently the cable faults increase at a faster rate than the generating capacity. The severity of short circuits also increases with increased generating capacity. Feeder reactors are particularly effective in reducing and localizing the effect of such short circuits. When properly proportioned feeder reactors are used, an increase or decrease of generator reactance has only a limited effect on the amount of kilovolt-amperes flowing into a fault. Bus section reactors in the generating station in connection with feeder reactors still further reduce and localize these effects, even when it might be more desirable to distribute their effect if other conditions permitted.

It would be desirable for many reasons to operate feeders in parallel at their substation ends, but such operation tends to increase greatly the kilovolt-amperes flowing into a feeder short circuit and to cause other feeders besides the one affected to trip out when overload relays with the usual settings are used.

Presented at the 299th meeting of the American Institute of Electrical Engineers, New York, October 9, 1914.

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USE OF REACTANCE WITH SYNCHRONOUS CONVERTERS

AN INSURANCE OF CONTINUITY OF SERVICE AND A PROTECTION OF APPARATUS

BY J. L. MCK. YARDLEY

ABSTRACT OF PAPER

The paper presents the results of overload and short-circuit tests made about two years ago upon some synchronous converters in circuit with auxiliary reactors.

Two entirely separate sets of tests upon two synchronous converters of widely different operating characteristics are described. In the one case the reactor is in the a-c. circuit and in the other in the d-c. circuit; yet in each it may be called, and in fact is, a protective reactor.

In presenting this original information the author, with a view to indicating its commercial application and hoping to provoke discussion, has endeavored to divide synchronous converter installations in a general way into classes with respect to the need or desirability of employing protective reactance, and also with respect to the general design or type of the reactor to be employed. In order to do this, synchronous converter installations are divided into a few general classes with respect to the character and exactions of the service conditions under which they are required to operate.

The paper was written shortly after the tests were made, but although much has been learned or written about protective reactors since that date, the author believes nothing has transpired to affect the value of these tests or to make it necessary to change the form in which it was originally intended to present them.

SYNCHRONOUS converter installations considered with regard to the relative importance of service and apparatus may be divided into three classes:

I. Installations where it is of prime importance to keep voltage on the lines at all times.

II. Installations where heavy overload sare frequent but where, to protect apparatus and accordingly maintain service, the voltage may be allowed to drop off during the overload.

III. Installations where high momentary overloads are frequent, unattended by appreciable voltage drop, but where brief even though comparatively frequent interruptions to service are not objectionable in order to protect apparatus.

I. Installations of the first class are found feeding the network

of circuits forming the distribution system of a metropolitan lighting and power company. Here the aggregate of power handled is the largest found in any power systems. The generating, transforming and converting stations are of the largest and most highly concentrated. The customers are the most numerous and the most widely distributed. The service required is the most varied in quality and quantity.

In such a system, handling an enormous aggregate of power, there is a large demand for service every hour of the twenty-four, every day in the year. Any failure, of however brief duration, to supply this demand means a great aggregate loss to the customer in money and convenience. In such a system, where immense quantities of power are generated in a concentrated generating station or group of stations, passed out through diverging feeders, transformed and converted in a plurality of substations and finally delivered 24 hours per day through a multiplicity of circuits to the ultimate consumer, the secret of satisfactory service lies in the smooth and orderly working of the various parts of the system. The difficulties in the way of securing uniform operation of such a quantity and variety of apparatus have been overcome only through great engineering skill. The method of operation is carefully prearranged and the various pieces of apparatus are started and stopped according to a schedule so as to make the service continuous. It is a tremendous undertaking to start and place in normal operating condition all the apparatus on the system when once it has been shut down. The utmost perfection of cooperation between men is required. A very severe strain is placed upon the power company's apparatus, while the delay and loss to the consumer incident to interruption is absolutely prohibitive. It becomes, therefore, a matter of necessity to maintain voltage on the customers' circuits at all times.

The direct-current feeders are interconnected at many points. A short circuit or ground on one feeder would trip out the overload breakers at a number of stations and thereby completely remove voltage from a comparatively large section of network. It is, therefore, considered preferable to omit automatic tripping features in the d-c. feeders. A short circuit or ground must, therefore, burn itself free or be eliminated only by some of the a-c. circuit breakers or apparatus letting go. In some of the very largest systems, the current-carrying capacity of the largest feeder is so small compared to the momentary overload capacity of the feeders to which it is tied, and of the apparatus supplying

them, that the trouble almost immediately clears itself. The total voltage is available at the scene of trouble. An arc of such magnitude is formed in consuming this voltage that the trouble shortly burns through. The voltage being consumed in the feeder having the fault, the remaining feeders continue supplied with scarcely reduced voltage and the apparatus running from them is scarcely affected. In these systems the trouble clears itself without seriously overloading the substation apparatus. In case the trouble should exist in the immediate vicinity of a substation so that substation would tend to carry the entire trouble, that substation would be saved from damage by the tripping out at the generating station of the a-c. supply feeders. The trouble would then, if it lasted long enough, be thrown on the remaining substations, which would more or less equalize it, and on account of their great capacity would be able to carry it until it cleared itself. There is, accordingly, no need of protective reactance in a substation of this character.

In systems of this general character but of somewhat smaller dimensions the current capacity of the largest feeder bears a less desirable ratio to the overload capacity of the feeders and apparatus supplying it. There are three immediate results:

(a) The trouble does not clear so quickly, as the current at the reduced voltage available at the trouble is not so great.

(b) The voltage on the other feeders falls off appreciably from the normal condition. Lights dim and motors slow down, but, in general, all apparatus continues to operate and a general shutdown does not result. The apparatus on the particular feeder in trouble probably stops owing to the greatly reduced voltage.

(c) Greater momentary overloads are thrown on all the supply apparatus. It is important, therefore, to give the apparatus characteristics such as to enable it to withstand these overloads satisfactorily.

The converting apparatus is usually a synchronous converter, though in some installations motor-generator sets are employed. These motor-generator sets have not the momentary overload kilowatt capacity of the converter. Usually the motor will pull out of step before the generator is dangerously overloaded. The synchronous converter will, in general, carry several times more kilowatt load than the motor-generator set before dropping out of step. It will carry so much overload before failing in this respect that the effect upon commutation must be considered. In the case of a shunt-wound motor-generator set, owing to the

poor voltage regulation of the generator, the current which can be commutated before the motor pulls out approaches more nearly the value of current which can be commutated by the converter. Some tests which will be given later on show that it is possible to throw six times normal full load current on some converters before they will flash over. It is obvious, however, that the actual possible limit of the converter is not the limit which must be observed in a commercial case. Assuming, therefore, that the converter will carry 400 per cent normal load current for a time comparable to that required for d-c. line trouble to burn itself free, it remains to equip the converter with auxiliaries which will enable it to escape all load in excess of this amount. There are several ways in which this may be accomplished when it is first known how much the voltage must be reduced.

1. In the case of a booster or split-pole converter the voltage can be lowered to the full buck value at any desired overload by means of relays in the d-c. circuit actuating the voltage-controlling element of the converter. On account of the time element of the relays and rheostat and the magnetic lag in the iron circuit of the converter this method is probably not quick enough.

2. A resistance short-circuited by a circuit breaker may be placed in the d-c. lead. The breaker would be tripped at some fixed value of current and the resistance placed directly in circuit. Owing to the time element of the ordinary overload circuit breaker this method is probably not quick enough.

3. With reactance placed in the a-c. circuit, a series field can be added to the main poles acting in opposition to the shunt winding, so that the power factor becomes badly lagging on overloads and the reactance produces a drop in voltage. This involves a series field on the converter, and the overload capacity of the converter is further limited by the wattless armature currents caused by the overload current in the series field.

4. A larger amount of permanent reactance may be placed in the a-c. circuit so that, even with a shunt-wound converter and approximately constant power factor, a great drop in voltage will occur at large overloads.

The fundamental objection which has been raised to apply to this last method as well as to the other methods suggested is that, owing to the inertia of the rotating part, the synchronous converter, in common with the direct-current generator, delivers an instantaneous direct current when the resistance of the external d-c. circuit is suddenly reduced, which can not be reduced

by any of the means suggested and which, particularly in the case of the converter, is likely seriously to affect the commutation.

Without debating this question, it is proposed to state that with a reactor of the air-core or unsaturated type in the a-c. circuit, there is no question but that the voltage drop across the reactor will follow instantaneously and exactly the alternating-current variations. It follows that, if the alternating current is at all times approximately proportioned to the direct current, a reactor may be employed in the a-c. circuit to limit the overload current which the converter can deliver.

Assuming a reactor of 30 per cent, the voltage impressed at the collector rings under several conditions of load is shown by the side A in the triangles of Fig. 1. The effect of the varying reactive drop B is to vary the phase angle of the voltage impressed at the collector rings. The converter must therefore be well equip-

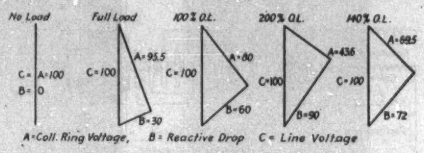


FIG. 1—SYNCHRONOUS CONVERTER—EFFECT OF 3 PER CENT REACTANCE IN THE A-C. SUPPLY CIRCUIT

ped with dampers so as to follow closely these phase variations. The line voltage is the constant vertical line C.

With these factors in mind, it is proposed to describe some tests which were made to determine the suitability of reactors for such service in connection with a converter under a certain set of known conditions.

A certain 250-volt three-wire Edison system enjoying the enviable record of having maintained voltage on the bus over a long period of years was the subject of this study. Ordinary feeder troubles have drawn the substation bus voltage down to 180 volts or 200 volts. In one or two cases of very severe trouble the bus voltage has been drawn down to approximately 160 volts, that is, to 64 per cent of normal, before the trouble cleared itself without a general shut-down. The amount of reactance required, therefore, for a converter on this system is such as will draw down converter voltage to 64 per cent of normal before the overload exceeds the limits of the converter.

A 250-volt converter was not available, but a 280-volt, 1000-kw., two-phase, 60-cycle, 600-rev. per min. commutating-pole booster converter with voltage range of from 240 to 320 d-c. was available. This converter was wired up to a bank of three-phase-two-phase transformers, in the circuit to which were placed three air-core reactors. The converter was loaded on rack resistors. The load was thrown on by closing a knife switch and was tripped off by means of a d-c. circuit breaker. One element of the oscillograph was arranged to show the voltage of the a-c. supply circuit outside of the reactance coils, for the purpose of showing that to a large degree the reduction of the d-c. voltage came about independently of any reduction in the voltage of the supply circuit. The other two elements of the oscillograph were arranged to show the direct current and voltage, which are the quantities of particular interest in determining the effect of the reactance. There was

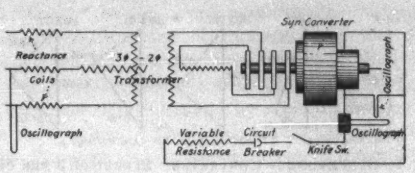


FIG. 8—CONNECTIONS FOR CURRENT-LIMITING REACTANCE

approximately 30 per cent reactance in the circuit in coils and transformer. There was a drop of not more than 5 per cent in the line voltage; but, due to the reactance and a large resistance drop in the converter, transformers and leads, the converter direct voltage at 8600 amperes output—that is, at 2.4 normal load—was reduced 50 per cent, to 140 volts. See Figs. 2, 3 and 5. Figs. 4 and 6 show the record of a second oscillograph. Fig. 4 was taken simultaneously with Fig. 3, and Fig. 6 with Fig. 5. They show the low-tension voltage at the collector rings and the voltage across the reactance coil in the high-tension circuit. Fig. 5 was taken to see if the hunting would dampen out, and the load was held a total of 8 4/5 seconds, which is much longer than the average line trouble takes to clear itself.

The synchronous converter employed was provided with relatively inefficient dampers, and there was marked hunting at approximately 80 alternations per minute when load was first thrown on, owing to the shift in phase angle of the voltage im-

FIG. 2 [YARDLEY]

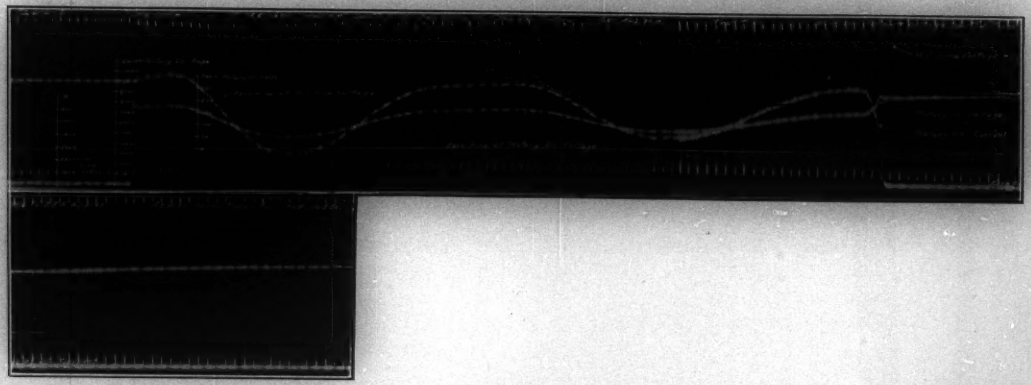


FIG. 3 [YARDLEY]

FIG. 4

[YARDLEY]

FIG. 5

FIG. 6

pressed at the collector rings. There was severe sparking at intervals corresponding to the period of hunting, which practically died out as the hunting ceased. The sparking was not so severe but that the load might very probably have been further increased or the reactance reduced, without exceeding the flashing limitations of the converter even with its ineffective dampers. This hunting and sparking would have been greatly reduced and possibly entirely eliminated if the converter had been provided with a damping winding of better design. There was no appreciable instantaneous d-c. generator effect, as the circuit was closed, which could be separated from the hunting action, and the tests were considered by a large number of engineers who witnessed them to show very conclusively the value of reactance used in such an application.

II. The substations on large or medium size interurban railway systems are in the class of installations which are subject to heavy overloads, where it is, in general, satisfactory that the voltage on the lines shall drop off and vary considerably during the overloads in order that the supply apparatus may be protected from injury. The size of the individual piece of converting apparatus is small compared to the capacity of the transmission system of trolley wires and feeders, though it is still large compared to the maximum momentary overload likely to be thrown on it. This is owing to the number of converter substations which will be in parallel and will divide any abnormal overload. In the case of a short circuit or ground on a d-c. feeder, there is great likelihood that the trouble will burn itself free as in the first class of systems, the capacity of a single feeder or trolley wire being small, relative to the size of the whole system.

These systems are large enough to have carefully worked out train schedules and to require close adherence thereto. Uniformity of trolley voltage is therefore an important requisite and the supply apparatus is given a voltage characteristic which continues to rise for all moderate overloads. In many cases compound-wound converters with suitably chosen series field and reactance are employed.

With a shunt-wound converter considerable voltage variation would be experienced unless the a-c. and d-c. reactance and resistance drops should happen to be quite small. With considerable series field and unsaturated reactor, a converter would continue to take on load, owing to its approximate straight-line rising voltage characteristics, and some means must be supplied to pre-

vent this load from reaching a value under abnormal conditions which would be injurious to the converter. There are disadvantages in having this protection in the form of a circuit breaker, since such a form of relief simply throws a greater overload upon the remaining converters on the system when one trips, and a general shut-down may result. It is much preferable to have the converters in each substation protected in such a manner that, in case a short circuit, grounded feeder, or abnormal load due to the bunching of cars occurs at any point of the system, the converters in the immediate vicinity will continue on the line, carrying all the overload they are able to carry. By providing a voltage characteristic which will droop before the critical safe overload is reached, the excess load is automatically distributed among the converters elsewhere on the system without actual interruption of service or drop in trolley voltage such as need affect the time schedule. The drooping characteristic on overload is obtained by employing a saturating iron-core reactor. Iron-core reactors have been installed in some of the largest substations in the country to equalize the load between transformer synchronous converter units having different inherent regulation characteristics. The use of them to divide the load between the different substations of a system, and by the voltage drop they produce thus to protect the individual substation apparatus from injury, thereby tending to secure continuity of service, is therefore but a wider application of the well-known functions of a well-known piece of apparatus.

III. The substations on small and medium size interurban railway systems are in the third class of installations. One converter supplies a comparatively long section of trolley line on which there is a comparatively small number of cars running at relatively long intervals. The drop in trolley line and feeder to points distant from a substation is considerable. Additional drop in reactance would be objectionable under normal operating conditions. The converter should have a rising voltage characteristic, therefore, to take care of the normal operating conditions. It must, however, have some protection from d-c. short circuits and abnormal overloads, particularly when these occur close to a substation. The overloads have a maximum so much greater than the average load and are, relatively, so infrequent that neither of the two previous methods of protection is best adapted. In this case it is necessary actually to get the converter off the line to prevent damage. The bigger the momentary

overload which can be carried before tripping off, the better, but momentary interruptions are not serious (particularly as in such a system the feeders and trolley wires are usually sectionalized so that a trip-out at one substation does not mean an interruption on the whole system) and the converter *must* be protected, at a temporary expense to service if necessary.

There is a limit to the current which any commutating machine will commutate without flashing over. This limit of instantaneous commutating capacity is usually way above the permissible capacity for any appreciable time limited by armature heating. The breaker may then be set considerably above any guaranteed overload value on such a system as we are now discussing, where the overloads, though very great, are very brief. A converter will also usually carry a much greater load momentarily than it will permit to be tripped off without flashing. Now there are certain auxiliaries which will greatly increase the severity of the short circuit to which the converter may be subjected without feeling it. If it is possible to throw overloads of five to six times normal on a converter before it will flash, the auxiliaries must prevent any excess beyond that amount. These auxiliaries consist of a reactor to introduce a time element in the rise of current when the short circuit is established, and a quick-acting circuit breaker. These two must be proportioned so that the trouble will be cleared before the current has reached a value which the converter can not safely commutate nor stand being tripped off. The reactance must be of the air core or unsaturated type and the breaker must necessarily be quite different from the ordinary d-c. carbon circuit breaker, which has a very appreciable time element.

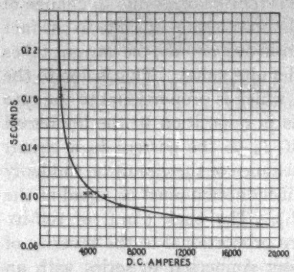
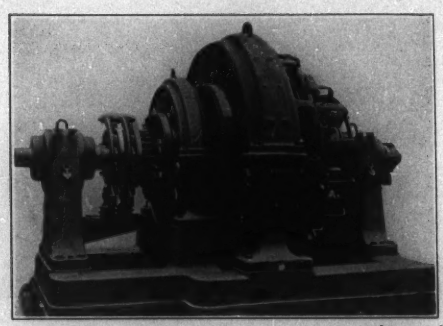


FIG. 9—TIME OF OPENING OF 1600-AMPERE, 600-VOLT CIRCUIT BREAKER

The ordinary carbon type d-c. circuit breaker has a time element which would require a prohibitive amount of reactance. Curve Fig. 9 gives the time element of an ordinary circuit breaker of 1600 amperes capacity. This gives the time for the mechanical operation only. Figs. 12-15 show the time taken by such a breaker to open the circuit.

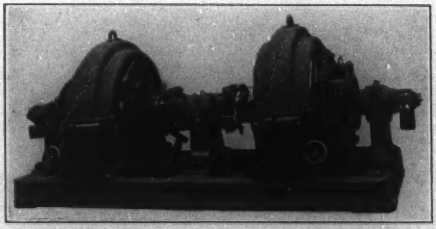
The high-speed circuit interrupter as developed by Messrs. Fortescue and Mahoney consists essentially of an ordinary single-pole breaker, the parts of which are accelerated by means of a heavy steel spring. After the spring has ceased accelerating, the momentum of the moving parts is gradually absorbed by means of a dash pot, so that the mechanism is not injured by sudden stopping. The breaker is provided with magnetic blow-outs and a special condenser-operated tripping device, the moving parts of which are designed to have a minimum of friction and moment of inertia.

The operation of the tripping device depends upon well known characteristics of a direct-current circuit, as follows: Under steady conditions of load the only resistance offered to the flow of current is the ohmic resistance of the conductor. If the circuit were absolutely non-inductive, current changes due to change of resistance would take place at an infinite rate, but due to the fact that inductance is always present in any circuit, the current takes an appreciable time to reach a definite value. This is due to the e.m.f. set-up by the inductance, which is proportional to the rate of change of the current, and is in opposition to the impressed e.m.f. of the circuit. Thus if I_0 be the current in a circuit whose resistance is R_0, if the resistance of the circuit be suddenly changed to R_1, the e.m.f. of self-induction must be equal at the instant of change to $I_0 (R_0 - R_1)$. The back e.m.f. of self-induction is therefore in a measure proportional to the severity of the short circuit. If a condenser connected in series with an electromagnet be shunted across the circuit, when the sudden overload or short circuit takes place there will be a drop in the e. m. f. across the condenser due to the inductance of the lines between the source of e. m. f. and the point at which the condenser and magnet are connected, proportional to $I_0 (R_0 - R_1)$, and the condenser will discharge through the magnet. By using a proper value of capacity the magnet may be made to operate at any required value of this back e. m. f., provided that R_1 be not greater than a certain value, which depends on the line constants of the circuit and the periodicity of the condenser and magnet. Should R_1 be greater than this value the trip will not operate, because it requires an appreciable time for the energy set free from the condenser to be transformed into mechanical energy in the magnet, and when R_1 is large the back e.m.f. lasts for a very short period. The tripping action is thus not only dependent upon the rate of change of the current but also on the



[YARDLEY]

FIG. 7—280-VOLT, 1000-KW., 60-CYCLE COMMUTATING-POLE SYNCHRONOUS CONVERTER



[YARDLEY]

FIG. 10—TWO 750-VOLT, 60-CYCLE SYNCHRONOUS CONVERTERS CONNECTED IN SERIES

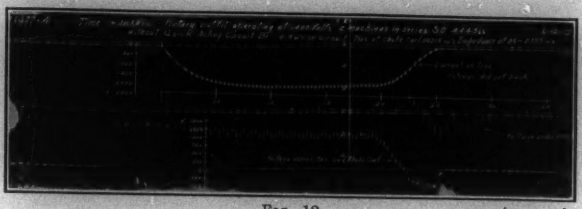


FIG. 12 [YARDLEY]

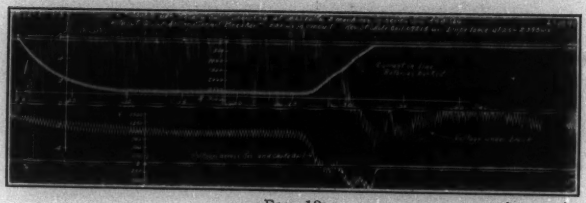


FIG. 13 [YARDLEY]

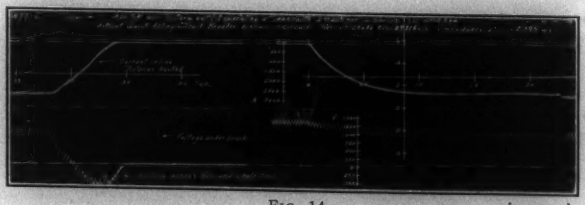


FIG. 14 [YARDLEY]

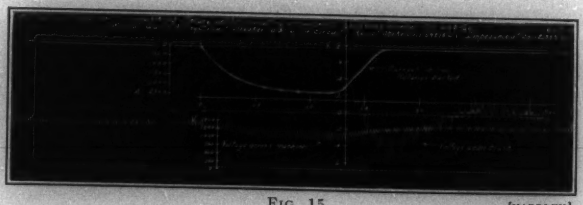


FIG. 15 [YARDLEY]

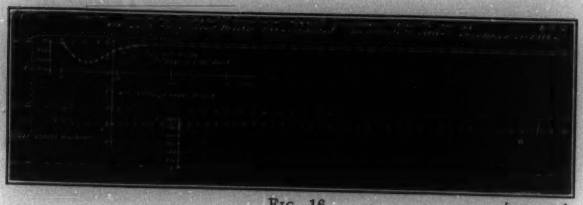


FIG. 16 [YARDLEY]

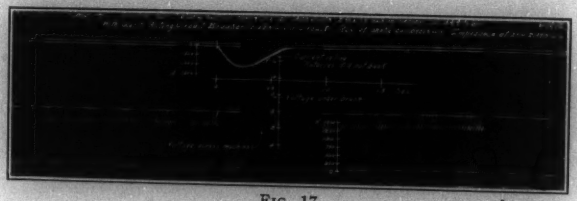


FIG. 17 [YARDLEY]

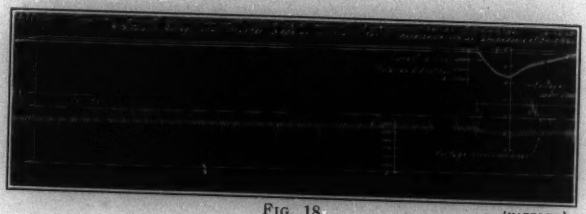


FIG. 18 [YARDLEY]

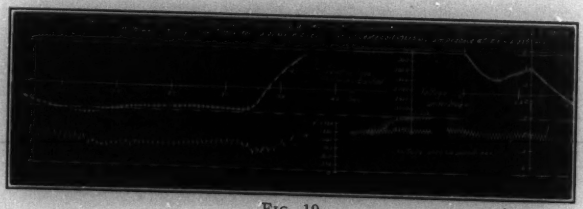


FIG. 19 [YARDLEY]

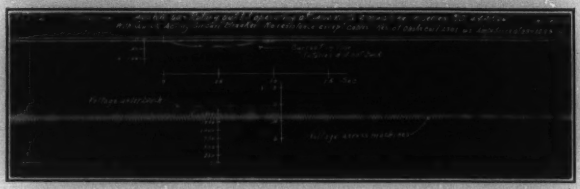


FIG. 20 [YARDLEY]

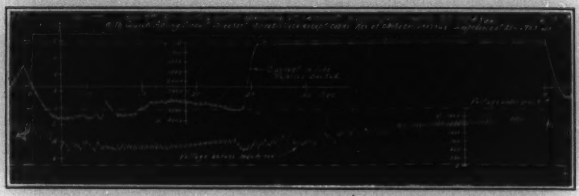


FIG. 21 [YARDLEY]

FIG. 22 [YARDLEY]

final value of the resistance. It may therefore be depended on to open the circuit only when the final value of the current would be such as to endanger the circuit.

For slowly varying currents, such as those due to the ordinary overloads, the regular overload tripping arrangement must be included in the breaker, as the condenser trip fails to operate under these conditions.

In case the current increases at such a rate that the ultimate value when the circuit breaker opens will be such as to endanger the circuit, additional inductance may be introduced in the circuit between the source of e.m.f. and the point at which the tripping gear is connected.

A series of tests was made to determine how severe a short circuit a synchronous converter would stand without flashing when protected by this quick-acting breaker and suitable

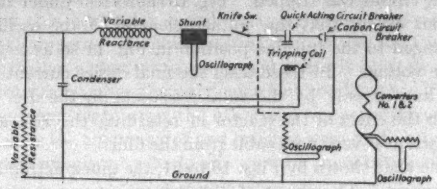


FIG. 11—SYNCHRONOUS CONVERTER WITH QUICK-ACTING BREAKER AND REACTANCE

operating reactance. The converter shown in Fig. 10 was used. This is a 1500-volt, 60-cycle set consisting of two 750-volt converters mounted on a common bed-plate and connected electrically in series. The armatures are mechanically separate, though a single bearing housing is used between them. The set is rated at 600 kw., 1500 volts, or 500 kw., 1250 volts, that is, it has a full-load current of 400 amperes. It is three-phase, with a speed of 1200 rev. per min. The oscillograms are marked 400 kw., though the machine will meet the higher ratings without exceeding standard temperature guarantees. The connections for test were made as per Fig. 11.

The oscillograms are shown in Figs. 12 to 22, Fig. 22 simply giving the time for Figs. 12 to 21. It shows a 25-cycle wave taken with the film run at the same speed, and is of no other value. The d-c. circuit of the converter was closed by means of a knife switch as shown in Fig. 11, the load consisting of resistance

which could be varied in amount. The reactor, of air-core type, was so constructed that its reactance could be varied by placing the sections in series or parallel.

In the first tests, as shown by Figs. 12 to 15, the quick-acting circuit breaker was omitted and the circuit was opened non-automatically by means of the carbon circuit breaker after a period long enough to determine whether the load itself would immediately result in flashing. For Figs. 12 to 14 one element of the oscillograph was connected as indicated by dotted lines in Fig. 11, to show the voltage across the resistor and choke coil. It will be observed from Fig. 12 that approximately 2100 amperes or 525 per cent normal load current was thrown on and tripped off this converter without flash-over. Figs. 13 and 14 show duplicate tests under heavier short-circuit conditions. The direct current rose to a steady value of 2600 amperes and the converter flashed when the circuit was tripped. Fig. 15 shows test under the same conditions except that the voltage element of the oscillograph was changed to the full line position in Fig. 11 so as to give the machine voltage. In these tests the final direct current was, of course, limited only by the total resistance in the d-c. circuit, although the effect of the reactor in retarding the rise and fall of the current is very noticeable from the films.

For the tests shown by Figs. 16 to 21, the quick-acting breaker was in circuit. The object of the reactor in connection with this breaker was to so affect the rate of increase of current that the breaker would be able to trip out before the current reached such a value as to cause flashing. Fig. 16 shows a test under the same short-circuit conditions as Fig. 15. Figs. 17 and 18 are with reduced resistance in the short-circuit path. As shown by Fig. 19, the resistance was then reduced to approximately 0.1 ohm. The quick-acting circuit breaker started to open the circuit and then arced across the terminals and short-circuited, so that the current—3500 amperes—was practically the same as though the quick-acting breaker had not opened at all. The quick-acting breaker was simply an experimental breaker and did not have the proper insulating clearances which would be given a commercial breaker to meet such conditions. The converter of course flashed over, as would be expected, when the circuit was finally tripped by hand. The next test, as shown by Fig. 20, was made with no resistance except that of the cables and the reactance coil, which latter amounted to 0.23 ohm, in the external circuit. The impedance was increased to 13 ohms. The

last test, as shown by Fig. 21, was made with the choke coil resistance of 0.05473 ohm and the cable resistance only in the external circuit and the impedance reduced to 0.903 ohm. This test was made for the purpose of showing how quickly the current would rise under such a short-circuit condition. The breaker opened as in Fig. 19 but arced across terminals and short-circuited, causing a final flow of current of 3900 amperes. It is interesting to note that the converter carried this 975 per cent current load at approximately 700 volts without flash-over, although it of course at once flashed over when the load was tripped off.

These tests are described to establish the fact that, if a properly designed quick-acting circuit breaker be used, and the proper amount of reactance be placed in the d-c. circuit, it is impossible to flash a converter over, as the circuit breaker will trip out the circuit before the current approaches the tripping out flash-over value. As shown by Figs. 12 and 13, this flash-over value for this particular converter is somewhere between 2100 and 2600 amperes. It is interesting to mention that as far as this particular converter is concerned there is scarcely need of such protection under the particular test conditions. The tests were made one right after the other and whenever the converter flashed over the commutator and brushes were so slightly burned that it was unnecessary to do any work on them between tests.

DISCUSSION ON "PROTECTIVE REACTORS FOR FEEDER CIRCUITS OF LARGE CITY POWER SYSTEMS" (LYMAN, PERRY AND ROSSMAN) AND "USE OF REACTANCE WITH SYNCHRONOUS CONVERTERS" (YARDLEY), NEW YORK, OCTOBER 9, 1914.

D. B. Rushmore: It is very difficult to consider the subject of reactors for power stations or feeders without studying the apparatus, such as generators, transformers, oil switches, protecting apparatus, etc.

As a rule, electrical disturbances are due either to high currents, high voltages or high frequencies; and high frequencies have, as a rule, an indirect effect of producing high voltages, so we have simply high currents and high voltages to contend with.

The use of reactors as a protection against high voltages is well known, and, I take it, is rather outside of the subject of the papers tonight; so we come down to the use of reactors as protective devices against high currents, and this is a subject which is comparatively new.

Those who have been associated with the building of transformers, know it is only a very few years since competition was based on excellencies of regulation. The transformers that regulated 1½ per cent were supposed to be very much better than those which regulated 2½ per cent. Now, however, the customer frequently specifies that the transformers must contain six or eight per cent reactance and even higher.

In designing generators, transformers, and to some extent converters and other synchronous apparatus, if you design for commutation and heating there will be a natural reactance that will fit these conditions, and without an abnormal design you cannot vary these reactances beyond a certain point. It is therefore a question discussed in many cases as to how much internal and how much external reactance there shall be.

The use of reactors in power stations also involves a study of feeder reactors, because one is so dependent upon the other. The injurious effects which these reactors are supposed to protect against are, first, the incidental rush of current, which is destructive to the windings and brings tremendous mechanical forces to bear thereon. Secondly, there is the heating effect, and it has been necessary to investigate to some extent the time which apparatus will stand very abnormal heating conditions when there is practically no chance for the dissipation of heat, but simply its absorption in the material in which it is originally generated.

Reactance is an evil; it is a necessary evil in some cases, but what we want is a reactance which is only there when it is required; so if someone will invent a reactance which is not a reactance until it is wanted, we will be greatly helped. That is, a reactance which is very low until the current exceeds a certain amount, and then is automatically raised to a very high value.

Philip Torchio: We hear so much talk of reactance now, because we neglected to take into account its importance in the past. For instance, very few of us used to consider when we compared the breaking capacity of a switch whether the short circuit was on a 25-cycle generator, or a 60-cycle generator. Provided it was the same capacity generator, we would have expected that the short circuit effect would be the same. But it makes a large difference in a feeder short circuit whether the current is 25-cycle or 60-cycle. At 60 cycles the reactance of the feeder would be 2.4 times that at 25 cycles, and the effect of short circuit would therefore be very different in the two cases.

I think the authors have covered pretty fully the benefits and advantages obtained from the use of reactors on feeders. I wish to add a few statements which have been perhaps omitted. One is, that the energy loss in feeder reactors is extremely small, and amounts to less than 1/10 of one per cent on 60-cycle, and less than $\frac{1}{6}$ of one per cent on 25-cycle transmitted power for a $3\frac{1}{2}$ per cent reactance.

In addition to limiting the current flowing into a feeder short circuit, the feeder reactance further increases the continuity of supply by preventing the generator bus voltage from materially dropping. As an example: Assume the 150,000-kv-a. bus with 8 per cent generator reactance given in the paper, with 5000-kv-a. feeders having 3 per cent reactance. The maximum feeder short circuit would cause only a momentary 9 per cent drop in the bus voltage. This is very essential in holding all of the synchronous apparatus in step on the system.

In very large systems the question of limitation in rupturing capacity of oil switches is a burning question. In this respect a 2 per cent or 3 per cent limiting reactance on the feeders would ensure the opening of the feeder short circuit under all conditions, without the least strain on the switch, or interference with the rest of the service.

The New York lighting companies found from their experience that some of the few serious generating station troubles were occasioned by failures of high-voltage motors driving auxiliary apparatus like station exciters, etc.

Recognizing this fact, they were pioneers in the use of feeder reactors by equipping all of the feeders supplying generating station auxiliaries with reactors, which have proved to eliminate entirely all of the serious troubles from that source.

Fig. 1 gives an illustration of such an installation, showing three sets of 250-kw. 8000-volt motor-generator exciters, each equipped with 2.5-kv-a. reactors.

The first station designed and equipped for busbar reactors and feeder reactors is the 201st Street station of The United Electric Light & Power Company, having an ultimate capacity of 130,000 kw., 8000 volts, three-phase, 60 cycles. Between each two sections of buses there are installed 18 per cent reactors (based on 30,000 kv-a.), and on each 4000 kv-a. feeder $3\frac{1}{2}$ per

cent reactors. The feeders are arranged in groups of two, each group being fed from a group switch. There are only two reactance coils for each feeder.

Fig. 2 shows one coil of one feeder in the front compartment, while the other coil is in the back compartment. In each of these compartments and on top of the existing coil there is a vacant space for the addition of a second coil for the second feeder not yet installed.

Fig. 3 shows a compartment with the double coil for the two feeders, both feeders of this group being already installed. On the right side are shown the terminals of the reactors through porcelain bushings.

Fig. 4 shows perhaps more in detail the construction of the feeder reactors and illustrates also the method of winding of the coil, which, after being saturated and baked, is placed in the holder with porcelain supports at top and bottom and sides, and ebonized asbestos board panel enclosures, for safety to apparatus and men.

In this connection I wish to lay stress upon the point of using insulated windings for the reactors. Coils with bare windings do not appear to me to be in keeping with the scrupulous separation by barriers and insulation of all high-tension conductors and wiring of a modern switchboard. Furthermore, I think that some insulation is necessary to protect the windings from foreign substances, vapors, accidental moisture and vermin. The difference in cost between bare windings and insulated windings is very trifling. The idea that bare windings can withstand higher temperature and therefore are safer is misleading, because it overlooks the fact that the protective reactance coils are always in circuit with other apparatus, like generator or transformer windings, cables and current transformers, all of which are insulated with fibrous materials and have less facilities to radiate heat than the reactance coils, and would burn out long before the insulation on the reactance coil would suffer.

From an extensive experience with insulated-winding reactors under most diversified conditions in this country and abroad, there is not a single instance of failure. Furthermore, some of these reactors have operated for several seasons when covered with soot and dripping wet from rain and snow blown on them, under conditions where a bare winding would have undoubtedly failed.

H. W. Buck: This question of reactance is certainly very important in alternating-current circuits, but I do not think that we should allow ourselves to be led to believe that all alternating-current systems should have reactors installed upon them. Simplicity is an excellent engineering goal to steer for, and our alternating-current installations are already too complicated, and reactors still further increase it. The acute necessity for reactance has been brought to our attention within

FIG. 1 [TORCHIO]

FIG. 2 [TORCHIO]

FIG. 3 [TORCHIO]

FIG. 4 [TORCHIO]

recent years through the development of such systems as that of the New York Edison Company and the Chicago Edison Company and others, where an enormous amount of power is concentrated in one generating station with the power transmitted over circuits of small inherent reactance, with the consumers located at comparatively short distances from the sources of generated power.

Here reactors are needed to improve the service and to preserve the integrity of the system against damage from abnormal magnetic forces. The enormous momentary flow of current in an alternating-current generator under short circuit, possibly ten or fifteen times what it is at the end of a few seconds, causes magnetic effects which are irresistible with a number of generators connected to the busbars and with possibilities for destruction in the stations which are very great.

Many instances of such destruction from magnetic forces have been noted and some which I have seen are as follows:

In one case a short circuit took place near a large power house. The busbars which were installed inside of a modern brick structure were blown out by magnetic repulsion through the brick of the surrounding structure, the busbar structure itself was demolished, and the copper of the busbar was blown 40 ft. or 50 ft. from its original location.

In another case, about 24 one-million-circular-mil single-conductor cables were racked on the wall of a run-way about 15 ft. wide. A short circuit took place in a manhole near the power house, with the result that every cable in the run-way was torn from the cast iron racks on which they were supported and hurled across the run-way, damaging the masonry on the opposite side.

A third case resulted in a short circuit of a power house of about 60,000 kw. normal capacity. The feeders through which the short-circuit current flowed were of ordinary three-conductor type, lead-covered. Under the magnetic stress prevailing several of the cables exploded, blowing the lead covering to pieces and demolishing sections of the eight-duct conduit in which they were installed.

I mention these instances to show the possibilities of the enormous magnetic mechanical forces which are available momentarily under short circuits from the large power houses, and the necessity of limiting the maximum flow of current under conditions of short circuit by the installation of reactors.

On long distance transmission systems where an overhead line intervenes between the generating station and the point where the power is used, reactance is not needed to prevent destruction at the receiving end, as the line itself necessarily has such high reactance that it automatically limits the flow of current at the terminus of the line to a safe maximum amount. Distribution systems, therefore, which are fed by long-distance transmission need reactors only for the purpose, as stated in

the paper, of controlling the regulation and for limiting the voltage disturbances on the system.

There is an important use of reactors on long-transmission trunk lines where a tap line is connected to the main trunk line, over which a comparatively small amount of power is supplied. Here it may be necessary to limit the amount of current which can flow over the branch line and so prevent its being a menace to the service on the main line. By installing a 5 per cent or 10 per cent reactor in the branch line, the service over the main line is not interrupted, and the effect of short circuit on the branch line is practically negligible to the trunk line service.

It is unquestionably desirable to install reactance coils on such large systems as that of the New York Edison Company to prevent damage from magnetic forces where the service is through three-conductor underground cables of small inherent reactance, where the maximum flow of current is limited only by the ohmic resistance of the circuit.

H. R. Summerhayes: Mr. Buck has just emphasized the necessity for simplicity in alternating-current systems. To my mind we should aim for simplicity in operation, and possibly we may accomplish that by the addition of apparatus in the form of reactors.

In Mr. Yardley's paper it was pointed out that on the Edison d-c. systems of the larger size, in which the whole network is connected in multiple, troubles are local, and they burn themselves out and do not result in a shut-down of the whole, or even of a large portion of the system. In fact, it is seldom that even the synchronous converter is shut down from these short circuits.

I believe the alternating-current systems are tending toward the same result. At present most of the large alternating-current systems are connected with radial feeders; that is, the feeders are not interconnected. Experience has shown that trouble will result if the feeders are interconnected in order to use the copper to the best advantage.

I believe that with the use of reactance in the proper localities, and the development of relays that has taken place, it will soon be possible to interconnect these systems and use the copper to better advantage; and that the operation will be similar to that of the direct-current system, in that the trouble will be localized.

One point brought out in the paper on feeder reactors, is that the busbar reactors must also be used, owing to the possibility of trouble in the station itself. That I think is a very important point.

There are other methods of using busbar reactors than simply connecting them between the sections. Some of the more recent ideas involve dividing large stations into one section for each generator, and not connecting those sections directly through reactors, but connecting each section through reactors

to a sort of tie bus. This I think is a considerable improvement over older systems.

Mr. Lyman concludes that it would be desirable for many reasons to operate feeders in parallel at their substation ends, but such operation tends to increase greatly the kv-a. flowing into a feeder short circuit and to cause other feeders besides the one affected to trip out when overload relays with the usual settings are used. I would suggest that this conclusion does not apply to all cases. The development in relays makes it possible to operate the switches selectively even where the kv-a. values at short circuit are very high. There are some cases, for instance, where it is sufficient to install reverse-power relays at the substation ends of the feeders and selective overload relays at the generating station ends. In other cases different expedients may be necessary. Generally the addition of feeder reactors makes it easier to make the operation of the relays selective.

Mr. Torchio invited discussion on the matter of insulation of reactors. Of course the great advantage of using insulation is that it makes the reactance compact, saving space in the station where space is of importance. The dimensions are reduced, as you do not have to allow such great distances between conductors to prevent surface leakage. On the other hand, the insulation on the conductors introduces a comparatively large amount of inflammable material at a point where it is exposed to the greatest amount of heat; that is, it is right in contact with the conductor, and all the heat must go out through that insulation. In case of weakness at the time of short circuit when the voltage across the reactance is high, a puncture or local flash-over might cause a considerable fire.

Therefore, I believe that insulation on the conductors should be avoided as a rule and used only where special conditions such as high working voltage, large number of turns or limited space for installation make a reactor with bare conductors impracticable.

J. J. Frank: In Mr. Yardley's paper reference is made to an automatic switch operating as a protective device. I question the ultimate value of such a mechanical device as an automatic protection in comparison with the value of the absolutely magnetic device found in these current-limiting reactors.

The controlling feature in the design of current-limiting reactors should be their function as a protection to generators, busbars, and feeder circuits. Every other feature in details of construction should be secondary to this dominating one. Both the mechanical and electrical designs may be widely different on reactors protecting generators and busbars, from those to protect high-voltage circuits, as referred to by Mr. Buck.

N. W. Storer: Mr. Rushmore has propounded a conundrum. He believes thoroughly in a larger reactance to keep down the violence of short circuits, as most of us now do, but he wants reactance that is reactance only when it is needed. The co-

nundrum then is, "When is reactance not reactance?" The answer is, "When it is short-circuited," and Mr. Yardley's paper has shown us how to secure this kind of reactance. One of the most noteworthy points in his paper is his reference to the tests of a quick-acting circuit breaker. I believe that the use of this circuit breaker to short-circuit a large part of the external reactance in the circuit will give just the combination that is desired. A certain amount of reactance must be in the circuit all the time, but given a quick-acting breaker such as described we can get all the benefit of a large reactance without its bad effects.

George T. Hanchett: When extraneous reactance was first introduced as a protective device, it always appeared to me as a piece of patch-work to cover up some of our previous mistakes. As Mr. Rushmore says, early specifications called for regulation par excellence, and having obtained, at great expense, rigidly constant potentials, we begin to counteract these by installing at further expense protective reactance.

We seem to have forgotten that it is very easy to build a transformer or generator of more open design by using larger clearances which will facilitate insulation and ventilation and reduce cost. In the case of feeders, particularly where it is desirable to interlock them, trouble flows from feeder to feeder through these interconnections which may well be reactors.

I was visiting the plant of a large transformer company a few days ago and was impressed to observe the tendency to insert magnetic leakage plates in transformers. These facts should be seriously considered when contemplating large reactances for the protection of large generators or transformers. With existing closely designed equipments, reactors are absolutely necessary.

Carl J. Fechheimer: The statement has been frequently made that iron in reactance coils is undesirable, as it saturates, such saturation occurring at just the wrong time unless a very large amount of iron is employed. The purpose of reactance coils is to prevent a prohibitively large current flowing; and if the value of reactance decreases as the currents increase in magnitude, due to the iron saturating, it fails of its purpose. Therefore, I also believe that in transformers, to which reference has been made, the same effect will come in. Similarly in the construction of generators we should not count on the effect of iron for increasing the reactance, trusting that thereby the great rush of current will be prevented.

It is interesting to note that the magnitude of the current which flows at the first instant on short circuit does not depend only upon the voltage induced just before the short circuit occurs and upon the total reactance in the circuit, but it is also affected somewhat by the point of the wave at the instant that the short circuit occurs. Therefore it is frequently a mistake to say that a certain percentage of reactance will

permit a definite current to flow on short circuit, unless one also considers the point of wave. This was brought up in a paper by Mr. A. B. Field read before this Institute.*

The question of the point of wave as well as that of the saturation in the circuit brings up the question: What is the effective internal reactance on short circuit? It is evidently a rather difficult matter to determine and it may be well for us in the Institute to decide upon some method of estimating what value should be considered correct. There may be other minor effects which influence this rush of current, such as leakage fields from other phases as well as the phase under consideration. It is my belief, however, that we can approach nearest to the correct value of effective reactance by measuring the reactance with the rotor removed—in the case of a star-connected stator, between neutral and terminal; with delta connection, with current in one leg only of the delta; and in the case of two-phase, across one of the phases. If, however, partly closed slots or equivalent thereof are employed, the effects of saturation cannot be neglected, and this makes it practically impossible to measure directly the reactance with this or other forms of construction which involve leakage paths that may saturate.

I would like to call your attention to the marked tendency that is at present evidenced toward securing high internal reactance, especially in large generators. Large reactance is usually obtained by the use of as large a number of turns in the stator as possible. This may be carried so far that the most economical design is not the one that is adopted. The most economical design would be that which would give the cheapest machine insofar as the relative proportions of copper and iron are concerned. One often has the idea that the larger the number of turns (the smaller the flux) the cheaper will be the machine. This is not necessarily so. In these machines it may be necessary, in order to increase the reactance by increasing the number of turns, to increase the cost. It is at times essential to use very deep slots and to laminate the conductors very carefully in order to prevent large eddy current losses.

Let us consider what are the leakage fields in the generator which are effective as reactance, it being understood that the reactance is that quantity which if divided into the electromotive force will give the current which will flow, the effect of resistance being negligible. These leakage fluxes are those which cross the slots, those which pass from tooth to tooth through the air above the slot, and those which interlink with the stator end connections. Any leakage fields from the rotor are of little or no influence. The effect of the presence of the rotor is in most generators of very small influence; any fluxes which pass from the stator through the air gap into the face of the rotor and back into the stator usually must cross the double air gap, which introduces very high reluctance.

*TRANSACTIONS A. I. E. E., 1912, Vol. XXXI, Part II, page 1645.

When a short circuit occurs on the alternator the tendency of the armature reaction is to wipe out the field. This tendency to cause the flux to die down induces in the field winding and in all other closed circuits in the rotor, electromotive forces which cause currents to flow, which in turn tend to prevent the dying down of the flux. In the case of the field circuit this current flows back through the exciter armature. There is therefore a tendency for substantially the same electromotive force to be generated in the stator conductors at the first instant after as before the short circuit occurs. The current that flows is that electromotive force divided by the reactance.

One is liable to infer, since the reactance of a machine with a large air gap is usually less than that of a machine with a smaller air gap, that this difference is due to differences in leakage fluxes which penetrate the rotor. We wish to point out that this conclusion is not correct. It is well known that the armature reaction of the machine is nearly proportional to the pole pitch and that the air gap is proportional to the armature reaction and hence to the pole pitch also. If the pole pitch is large, corresponding to a high-speed machine, the number of turns in the stator is also small, which means that the reactance is low. Hence low reactance generally accompanies large air gaps.

Mr. Woodward: Is there any circuit breaker developed which will open a circuit in 0.01 of a second? The damage is done in the first one-half cycle, and the circuit breaker would have to operate in 0.01 of a second. We can cut off that portion of the relay curve which is not selective, and reactance is a big factor in that way.

Mr. Howard: I note on Fig. 11 of Mr. Yardley's paper, that there is another circuit breaker in connection with that quick-acting circuit breaker. Does this quick-acting circuit breaker require one more, or is this merely a test condition?

Philip Torchio: I will say a word in explanation of my recommendation of insulating the windings of reactors. I do not have reference to any specific design in any way. I said, take the reactors as you build them now, but on the windings put on a light insulation. I am not recommending this to provide against the rises of potential; I assume that that has been taken care of in the design; my idea is to bring up the point of having some covering as a protection against dust and foreign objects.

I consider that essential, as in stations where we put in busbars and leads separated by brick compartments, we should not connect bare coils without separation between the windings, or something to prevent accidental contact causing short circuit.

Mr. Burnham: Several years ago I conducted a number of tests similar to those described in Mr. Yardley's paper, to determine the use of reactance for protecting synchronous converters. The results of these tests seemed to point only to one solution, and that was the availability of the quick-acting cir-

cuit-breaker. The converter cannot be protected from flashing unless the first current rush is cut down. It does not make any difference what reactance you use on the alternating-current side, this will flash over if it is a dead short circuit.

To obtain the extreme condition, a converter was short-circuited immediately after being disconnected from the a-c. circuit. It took about twelve times full load current, and flashed over. The current slowed down immediately, so no damage was done.

That shows the converter will flash over regardless of what you do to the a-c. circuit. To prevent the current rising when the converter is short-circuited, reactance was tried, but it was found that a prohibitive value of reactance was necessary in order to keep the current down for a sufficient length of time for ordinary circuit breakers to act. To use an amount of reactance that would be a reasonable size, and which could be used commercially, the circuit breakers would probably have to act three times as quickly as any we have now.

It might be of interest to give some of the results of the tests with reactance in circuit. Sixty per cent reactance gave 21 times full load current. Twenty-two and a half per cent reactance, which is probably the maximum commercial, gives 28 times full load current. No reactance gave 33 times. With the machine running disconnected, at full speed, the normal feed, the short-circuit current varied from seven to twelve times full-load current, according to the winding.

When the machine was connected with the field windings, the minimum current was obtained. This looks contradictory on its face, but the effect of the reactance of the series field was much greater than the compounding effect.

The test with the non-inductive shunt equal to the resistance of the field, gave about twelve times full load current. As a plain shunt-wound machine, it gave eleven times.

All of these values are above the flashing point as given by Mr. Yardley, as being four to six times full load current.

In Mr. Yardley's paper is the statement "It follows that if the alternating current is at all times approximately proportioned to the direct current....." The latter portions of the paper are based on this assumption. I do not find this to be true. The direct current is always decidedly higher than the alternating current for the first period of the short-circuit.

I think that is shown too on some of these curves. In the first set of curves, Figs. 2 and 3, it will be noted that the direct current is perhaps 40 or 50 per cent higher for the first six or seven cycles than it is for the following time.

It is also stated: " there was no appreciable instantaneous d-c. generator effect." The curves I have just mentioned show there is an appreciable d-c. generator effect for the six or seven cycles. The d-c. output is appreciably higher than the a-c. input. The direct current is decidedly higher at the beginning of the short circuit.

Another statement made is that, "with considerable series field and unsaturated reactance, a converter would continue to take on load owing to its approximate straight-line rising voltage characteristics." An unsaturated reactance would give a greater tendency for it to bend downward, rather than to go in a straight line. This is due to the increasing proportion of the energy current to the wattless current, which bends the converter voltage out of phase with the line voltage, and reduces it in value.

Another statement is, "The drooping characteristic on overload is obtained by employing a saturating iron core reactance." I believe the reference is true, that you get greater drop if you use a reactance that does not saturate. The smaller the reactance the flatter the regulation curve.

J. L. McK. Yardley: The first question was in regard to the possibility of building a quick-acting circuit breaker which would operate in 0.01 second. If you will refer to Figs. 16 to 19, you will note that the time is given and that this particular circuit breaker operated within 0.015 second. I believe it is only a matter of closer adjustment to reduce the time to less than 0.01 second. In fact, I understand later tests show such to be the case. This breaker of Messrs. Fortescue and Mahoney is really so unusual as to deserve a paper devoted entirely or primarily to itself.

In regard to the second circuit breaker shown in Fig. 11, of the ordinary carbon break type of construction, it was desired to secure a comparison between the results obtainable with the two types of circuit breakers. Figs. 12 to 15 should be compared with Figs. 16 to 19. For convenience, only, both breakers are shown in Fig. 11.

Mr. Burnham has described some tests made upon a synchronous converter with reactance in the a-c. circuit under the condition of dead short circuit. Of course, as I have mentioned in my paper, a synchronous converter will flash over under such a condition. The figures given by Mr. Burnham for the current delivered at the instant of short circuit are interesting and agree with the results of other tests I know of. Fortunately, however, as brought out in the paper, the condition of dead short circuit is not met with on distributing systems of the class for which I have suggested the use of reactance in the a-c. circuit to the synchronous converter as a protection. Obviously, the actual operating conditions to be experienced on any system for which any sort of protection is desired must be carefully analyzed before a recommendation is made. In my use of the term "at all times" to which Mr. Burnham objects, I mean at all times which actually occur in practise on such a system as that under consideration. Perhaps my use of such a broad term is unfortunate, but I have in mind strictly commercial conditions. Nowhere in my paper do I deny the existence of a d-c. generator action in a synchronous converter when it is short-circuited. What I do claim is that this thing has been a regular bugaboo in the minds of some

people, whereas in the majority of practical cases of the class of the one I have analyzed it is negligible. In the practical case the reduction in resistance of the d-c. circuit is not either sudden enough or great enough for the rotating element of the machine to give up appreciable power, whereas reactance in the a-c. circuit is actually a protection against excessive power coming from the supply line at such a time.

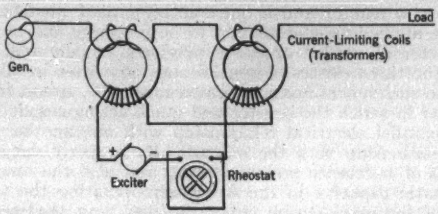
I don't exactly understand Mr. Burnham's objections to other parts of the paper. I believe it is common knowledge that the voltage regulation of a shunt-wound converter is better if the reactance in this a-c. circuit saturates as the load increases, than if it does not saturate, and that the reverse is true in the case of the compound-wound converter, the series field of which has not been too heavily shunted.

Before finishing, I desire to call attention to what seems to me the most obvious conclusion to be derived from the tests I have described. I think they point to one particular combination of a resistor, a reactor and a quick-acting circuit breaker which could be applied as a protection to both service and apparatus for the case of sudden excessive overloads equally well in any one of the three classes of synchronous converter installations. I refer to such a combination located in the d-c. circuit from the converter in which the resistor and quick-acting circuit breaker are in parallel electrical relationship with one another and in series relationship with the reactor. By properly varying the amounts of resistance and reactance, and also the amount of electrostatic capacity in the condenser operating the tripping device of the quick-acting circuit breaker, any predetermined sudden overload may be protected against. I have already recommended such equipment for one or two installations of converters where flash-overs have occurred due to sudden excessive overloads or short circuits; but so far as I know this arrangement has not, as yet, given a practical demonstration of its worth. It is apparent that the reactor in the d-c. circuit is no protection against an excessive overload gradually accumulated. It is further obvious that to be completely protected against an excessive overload, gradually as well as suddenly attained, a reactor must also be placed in the a-c. supply circuit. A careful analysis of the operating conditions, I believe, will always show that any desired degree of protection may be attained; but it will usually show that complete and absolute protection is not warranted or even desirable. It will show in many cases that the degree of partial protection suggested in my paper for the different classes of synchronous converter installations is a matter of economy and well worth attaining.

John B. Taylor (by letter): Protective reactors have a voltage across terminals varying from zero at no load to approximately 58 per cent of line voltage under short-circuit conditions. This "drop" in the coil disturbs the voltage regulation by a greater or lesser amount, depending on the power factor of the load, and under the most favorable conditions is a detriment.

Accordingly, coils without iron cores are used so that the coil-drop under usual running conditions will not be an abnormally large part of the total drop when short circuit occurs. Iron is omitted for the well-known fact that its permeability falls off with increasing magnetic flux density—in other words, it becomes saturated.

As there is no known material with magnetic characteristics reversed from those of iron, *i. e.*, increasing permeability with increasing density, the air-coil with straight-line characteristic, through having uniform permeability, is preferred. It is possible, however, to arrange matters, using iron itself as core, so that the desirable reversed characteristics result. This is accomplished by having the iron core saturated independently of the alternating-current circuit which the coil is to limit. If the core is completely saturated no flux change will follow the alternating current unless this has sufficient number of ampere-turns to



overcome those above the saturation point in the auxiliary exciting circuit.

The accompanying diagram will make the arrangement clear. For simplicity, a single-phase instead of a three-phase circuit is shown. Two coils which are practically standard transformers are connected so that the direct-current saturating circuit does not form a short-circuited secondary. These serve alternately to give the desired counter e.m.f. under overload or short-circuit conditions when the direct-current ampere-turns are overbalanced by the alternating-current ampere-turns. The auxiliary saturating equipment is obviously an added complication and expense but the arrangement effectively limits current on a short circuit to a definite relatively small value without excessive drop in the series coil under normal conditions. Furthermore, the current on short circuit is readily controlled by varying the current in the saturating circuit.* If the saturation circuit is opened, the load circuit is practically opened also through reduction of current to magnetizing current of the choking transformers.

H. R. Summerhayes (by letter): Referring to the arrangement No. 4 of placing a large amount of permanent reactance in

*See similar diagram and oscillograms in A. I. E. E. TRANS., Vol. XXVIII, Part I, 1909, pp. 729-731.

the a-c. circuit of shunt-wound synchronous converters in order to obtain a considerable drop in continuous voltage at overloads, tests of this arrangement are described, and oscillograph records, Figs. 2 to 6, are submitted with the paper.

To my mind these oscillograph records do not show that any appreciable reduction of continuous voltage was effected by the addition of the reactance in the a-c. circuit until such a long time had elapsed that the protection was ineffective. In oscillogram Fig. 3, when the load of about 11,000 amperes is applied, this load increases from zero to 10,000 amperes in a short time; practically instantaneous as compared to the scale of the oscillograph, and the continuous voltage drops from 280 to about 175 in the same short interval of time.

The oscillograph in Fig. 4, which was taken at the same time as Fig. 3, shows that when the load is applied, the voltage across the collector rings of the synchronous converter drops rather gradually; that is, several cycles are required for this voltage to drop from about 310 to 220. It is apparent that this drop in the impressed voltage across the a-c. collector rings is due to the phase displacement shown in the diagrams, Fig. 1; this phase displacement means that the armature of the synchronous converter actually drops back in space from the position of the revolving flux and this mechanical displacement requires several cycles. This slow reduction in the voltage across the a-c. collector rings, which is evidently reduced by the phase displacement caused by the increase of current through the reactance, does not correspond to the sudden drop in continuous voltage at the time of the application of the load, which is apparently due entirely to IR drop in the armature and external circuit.

During the period of several cycles in which the alternating voltage across the collector rings is being reduced from 300 to 200, the continuous current and voltage remain practically constant. In fact a slight increase is shown in the current.

It is evident that if the d-c. load thrown on had been of a value sufficiently great to flash over the converter, the converter would have flashed over irrespective of the reactance in the circuit, since the original value of the d-c. load lasting about a tenth of a second was not limited by the reactance. One effect of the reactance appears to have been to increase the phase displacement and, in connection with the inertia of the armature, to start hunting. It further appears that the instantaneous value of d-c. load lasted long enough to trip a circuit breaker. The reactance undoubtedly reduces the continuous current after a period of several seconds, as, from oscillograph Fig. 5, it appears that the final effect of the reactance at the end of the period of hunting was to reduce the continuous current from the initial value of 10,200 to the final value of about 9000, but the action is too slow to protect the converter from flashing over or to prevent the circuit breaker from operating.

Presented at the 300th meeting of the American Institute of Electrical Engineers, Philadelphia, Pa., October 12, 1914, under the auspices of the Committee on Use of Electricity in Marine Work.

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SUBMARINE SIGNALING

THE PROTECTION OF SHIPPING BY A WALL OF SOUND AND OTHER USES OF THE SUBMARINE TELEGRAPH OSCILLATOR

BY R. F. BLAKE

ABSTRACT OF PAPER

Submarine signaling has been greatly advanced by the introduction of a powerful sound transmitter and receiver called the "Fessenden telegraph oscillator." By means of this, telegraph messages can be sent and received through the water by moving ships and for short distances speech can be transmitted, icebergs can be located, and soundings taken instantaneously.

The apparatus consists of an oscillating electric motor-generator which has a strong electromagnet surrounding a central core on which is an alternating-current winding. Between the core and the magnet is a copper tube which acts as a closed secondary to the core winding. This copper tube is attached to a large diaphragm. When the alternating current passes through the core winding it induces a current in the copper tube, which, being free to move, vibrates back and forth, thus setting the diaphragm in vibration.

This apparatus is installed in a ship so that the face of the diaphragm is in contact with the water and its vibrations set up sound waves in the water. Signals have been sent a distance of 31 miles.

The oscillator can also be used as a receiver. Sound waves striking against the diaphragm cause the copper tube to vibrate, thereby generating a current in itself which is induced in the core winding. A telephone receiver in the armature circuit enables the observer to hear the sound.

COMPARED with other forms of transportation, the amount of energy necessary to transport water-borne freight is very small and its cost would be cheap indeed if it were not for the dangers of the sea. We have fogs and rocky coasts, shoals and icebergs, currents and storms to guard against, and these add immensely to the expense. Of this we have had a very recent instance, for, as the result of the loss of the *Titanic*, vessels carrying passengers are now constructed with a complete double bottom extending above the water line; in other words, instead of a single ship, we must now have two complete ships, one en-

tirely enclosed by the other. And the loss of the *Empress of Ireland* indicates that even this may not be adequate.

Bit by bit the dangers which beset the early navigators have been overcome. The chart told him the best course to take from one point to another. The mariner's compass enabled him to maintain his course when the stars were blotted out by clouds. With sextant and chronometer he located his position, with log and soundings he guarded himself when a sight could not be obtained. More recently wireless telegraphy has enabled him to call assistance in time of danger. But with all this, many dangers remain. The more important of these are due to fog.

The North Sea, the English Channel and the Grand Banks, the New England coast, the western coast of the United States, British Columbia and Alaska, and other points are all of them subject to fogs, sometimes lasting for weeks at a time, and it is therefore not surprising that thousands of lives are each year still lost at sea.

And there is not only loss of life; the pecuniary loss is also very great. It is no unusual occurrence for a score of steamers to be tied up at one time, unable to enter harbor on account of fog or of the combination of fog and rough weather.

In such a case, the loss to the steamship companies in interest and depreciation on ships and cargoes and in wages may easily amount to more than fifty thousand dollars per day, and this loss occurs not once but frequently during a year, and on many routes.

In addition to this, the danger of collision in fog adds very considerably to the cost of insurance, and some of our worst disasters have occurred in this way.

Aside from those dangers peculiar to fog, there remains a number of others. A continuance of cloudy weather or abnormal ocean currents or both, may throw the navigator out of his reckoning and place him on a rocky shore a score of miles away from the safe route he assumes himself to be following.

Icebergs still remain a menace in spite of all the efforts which have been made to guard against them. From time to time, statements have been made that apparatus has been devised which is capable of locating their presence, but in every instance in which such apparatus has been tested it has proved a failure.

The history of systematic marine protection by means of lighthouses and beacons does not go back very far. It is true that there were a few lighthouses such as the Pharos of Alexandria

centuries ago, but even in quite recent years a European Government received a petition for compensation from the inhabitants of a sea coast district on the ground that the erection of a lighthouse had deprived them of one of their principal sources of income, to wit, luring vessels on nearby shoals by means of false lights.

The systematic employment of sound signals for marine protection is of still more recent date and has never been carried out fully, in spite of the fact that many of our greatest scientists, for example Tyndall and Rayleigh, have devoted special attention to this matter.

One reason for this is that sound signals produced in air are very erratic in their range and intensity, so much so as to be on many occasions absolutely misleading. This is due to the fact that when a fog-horn is blown, the sound may be carried by the wind or may be reflected or refracted by layers of air of different densities, with the result that the sound may be audible many miles away while there may be a zone of complete silence extending from a few hundred yards in front of the signal to a distance of four or five miles.

As this phenomenon is by no means infrequent, the result has been to discredit more or less this type of signal, and it will be evident that the knowledge that a siren had been installed at a certain dangerous point might prove a source of danger instead of a protection.

As already stated, many eminent men have worked upon this problem, but it was not until Arthur J. Mundy, of Boston, suggested the use of water instead of air as the medium for transmitting signals and proved its value by practical demonstration that any great advance was made. Water has many advantages over air for this purpose.

1. In the first place, it is free from the dangerous zones of silence which occur when the signals are produced in air.

2. In the second place, the absorption of the sound is much less in water and consequently the signal is not only absolutely reliable but is transmitted to a distance many times greater than when it is transmitted through air.

3. The sound is not carried away by the wind in stormy weather, as is the case with the siren.

4. It is not affected by atmospheric disturbances, as in the case of wireless.

5. It permits of the accurate determination of the direction

from which the sound is proceeding, which is not the case with either the air siren or wireless telegraphy.

Some recent instances where ships have signaled by wireless that they were in distress but have had to remain without assistance for many hours, and in one instance for more than a day, because their location could not be determined by the vessels coming to their aid, will be familiar to every one.

All these advantages indicated clearly years ago the advisability of developing apparatus for signaling by means of sound waves transmitted through the water itself.

But it is one thing to conceive the idea, and another thing to develop a practical system, and it may be of interest to know that up to the present time the sum of a million dollars has been invested in developing submarine signaling, so far without monetary return.

The first method which was employed for producing the sound was through the striking of a bell and the method of receipt of the signals was by means of a microphone attached to the skin of the ship. Neither the original bell nor the original microphone attachment was satisfactory.

It would be impossible in the space permitted to discuss even briefly the innumerable experiments made with different sizes of bell, with different materials for the bell, with different methods of producing the blow, the precautions taken to eliminate electrolytic action, with different types of microphone, with different methods of mounting the microphone on the side of the ship, with the experiments made to minimize water and other noises. It will be sufficient to say that finally the work of Mundy, Wood, Fay, Williams and others resulted in a completely practical system.

The submarine bell in use on the lightships is actuated by compressed air stored in a reservoir. The actuating wheel has projections mounted on it so that when the wheel revolves a number of strokes follow each other, the different intervals being peculiar to the different signal stations so that the captain of a ship by counting the strokes of the bell can determine what lightship is producing the sound.

In order to receive the sound, it has been found absolutely necessary to suspend the microphone in a tank of water, for this is the only method of cutting out the water noises and the noises due to machinery, etc., on board the ship, which otherwise drown out the sound of the bell.

One of these small water tanks, containing a microphone of a special type, is attached to each side of the bow inside of the ship. From each tank wires are run to a device which is called the indicator box, so arranged that by throwing the handle to one side, the starboard microphone is connected to the telephone, and by throwing the handle to the other side, the port microphone is connected.

It will be obvious that once the bell is picked up, the captain has only to turn his vessel until the sound is heard with equal intensity on each side, to know that his ship is then pointing in the direction from which the sound is coming, and in this way he can take compass bearings of the lightship on which the bell is situated.

The importance of this method will be at once perceived. No matter how stormy or how foggy the weather may be, it enables the captain of a ship, on making land, to obtain at once the compass bearings of the nearest lightship or lighthouse fitted with a bell.

How many vessels and how many lives this device has saved even in the few years during which it has been in use, it would be impossible to tell. Less sensational than the wireless telegraph, it may be questioned whether its actual practical utility to the merchant marine has not been greater.

Compressed air, or an electromagnetic mechanism, may swing the hammer, or the bell may be operated by the waves themselves. A type much used is a bell buoy which may be anchored off a shoal, and will give submarine warning day and night without further attention. A large vane extends from one side of the mechanism. As the buoy swings up and down in the water, the vane by means of a ratchet compresses a spring which automatically releases and operates the bell hammer.

It will be evident that, even if no further development had been made, the system would be and is a complete and practical one. Its universal adoption would greatly minimize if not entirely prevent disasters due to errors of ship position.

But with the very success of this system, it became evident to those in charge of its development that still further advances might be conceived as possible, especially in three directions.

1. Suppose the sound-producing apparatus could be so constructed as to be operated from moving ships by a telegraph key. If this were achieved, it would be possible for one ship to signal to another in fog, to communicate its position, its

direction and its speed, and eliminate all dangers of collision. It would also be possible to signal between submarines or between battleships and submarines, and to communicate between battleships in action without interference from the enemy and though all masts were shot away.

2. Suppose the range of the sound-producing apparatus could be extended so as to cover a radius of 25 or 50 miles. Then it would be within our power so to encircle the coast of every nation, with what has been felicitously termed "a wall of sound," that no vessel under whatsoever circumstances of loss of reckoning, of variable currents, of fogs, and storms could approach the coast without being warned of that fact and notified of its exact position on that coast and of the direction of the nearest lightship.

3. If the sound-producing apparatus could be constructed so as to be actuated by telephonic currents, it would be possible to transmit speech through the water.

It will be of interest to consider some of the difficulties which had to be overcome before the desired results could be obtained.

The most serious of these obstacles was the fact that water is almost incompressible.

Now since sound is a compressional wave in the medium through which it is transmitted, it is evident that any apparatus which is to transmit sound through water must be capable of exerting very great force. In the bell, this is accomplished by the hammer blow of the clapper, and any electric or other apparatus which is to be used for submarine signaling must have a force comparable with that produced by the impact of a hammer on an anvil.

A second and very grave difficulty arises from the fact that if the water is to be compressed, some material object must be set in motion to compress it, and that object, which must have sufficient mechanical strength to stand the stress, and must therefore be of considerable size, must start from rest, reach its highest velocity, and come to rest in one-thousandth part of a second, if a musical note having a pitch of five hundred per second is to be produced. The forces of acceleration thus necessitated are very large.

A third difficulty arises from the fact that in order to telegraph a a speed of twenty words per minute the time allowable for a single dot is very small. As the average word consists of five letters, and the average letter has a length equivalent

to seven dots, an apparatus capable of telegraphing at the rate of twenty words per minute must be capable of making seven hundred dots per minute, or a single dot in something less than one-tenth of a second.

If the signal is to have individual quality, so as to be readily distinguishable from other noises, and so as to be separable by resonance from other notes, each dot must consist of at least ten impulses.

Thus we arrive at the conclusion that whatever device is used, it must be capable of producing at least 100 compressional waves in a single second, in order to telegraph satisfactorily at the rate of twenty words per minute.

If this same apparatus is to transmit speech through the water, it must be still more rapid in its action and must be capable of producing several thousand compressional waves per second.

The above were the three main difficulties in the way. Of course there were many others—for example, the apparatus must not weigh too much; it must not be affected by water or change of temperature; it must be simple in construction; it must be easily applied to the ship; positive in its action; must not require adjustment after being once set up and must be able to stand all kinds of ill-treatment at the hands of unskilled operators. It will be unnecessary to go over the ground taken by the development, and we will therefore proceed at once to describe the apparatus as finally developed by Professor R. A. Fessenden.

The device used is termed an oscillator and its construction is shown in cross-section in the drawing, Fig. 1.

In the drawing, the iron of the magnetic circuit and the copper tube are shaded. The magnetizing coil is cross-hatched. The moving part is the copper tube *A*. This lies in the air gap of a magnetic field formed by a ring magnet *B*, built up in two parts, as shown in longitudinal section in Fig. 2.

The ring magnet is energized by the coil *C*, and produces an intense magnetic flux which flows from one pole of the ring magnet across the air gap containing the upper part of the copper tube, thence through the central stationary armature *D*, thence across the other air gap to the lower pole face of the ring magnet and thence through the yoke of the ring magnet back to the upper pole face.

This field is very much stronger than that in the ordinary dynamo, there being more than 15,000 lines for each square centimeter of cross-section.

Around the armature is wound a fixed winding, which we will call the armature winding, and which is reversed in direction so that one half of the winding is clockwise and the other counter-clockwise.

When an alternating current is passed through this armature winding, it induces another alternating current in the copper tube.

Only by this construction has it been found possible to obtain the enormous force and rapidity necessary to compress the water

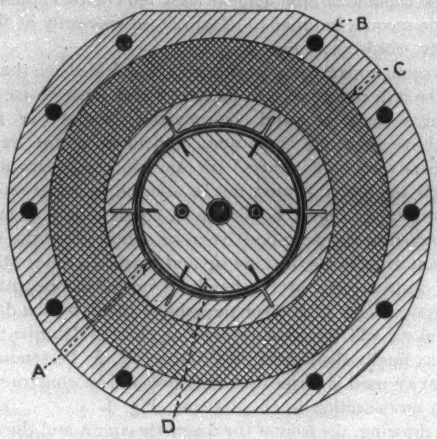

FIG. 1

and to overcome the inertia of the moving parts of the mechanism.

In order to apply this force to the work of compression, the copper tube is attached to solid disks of steel, which in turn are attached to a steel diaphragm one inch thick which may be made part of the side of the ship. In practise the tube is provided with lugs, and is held between two disks drawn together on the tube by a one-inch vanadium-steel rod and a right- and left-handed screw thread.

Telegraphing is accomplished by means of an ordinary telegraph key placed in the main armature circuit.

Although an ordinary telegraph key is used, there is no

sparking at the contacts. This may surprise electrical engineers familiar with the sluggish action and vicious arcing commonly found associated with the operation of electromagnetic apparatus of this size and power, more especially in view of the fact that a very high frequency is used, five hundred per second, and that there is no laminated iron used in the construction of the apparatus.

The secret of this lies in the fact that the armature has substantially no self-induction, and no eddy currents are generated in the apparatus. This is because the copper tube forms, as will be seen, the short-circuiting secondary of a transformer, of which the armature winding is the primary.

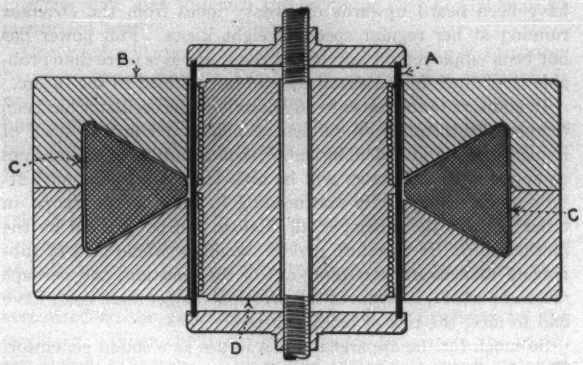

FIG. 2

This eliminates the self-induction of the armature winding. In addition the upper and lower portions of the winding are wound in opposite directions, and therefore there is no mutual induction between the field coil circuit and the armature circuit. With this construction, the amount of magnetic leakage in the armature circuit is very small, only a trifle more than if the armature core were of wood, and as there is no alternating magnetic flux in the iron, there are no eddy currents.

As regards the capacity in kilowatts of this apparatus, it is large. The armature, being wound in grooves in the armature core, so as to withstand the mechanical forces acting upon it, is well cooled.

The copper tube has no insulation to be affected, and on account of its large cooling surface and high permissible temperature of operation, can carry very high currents without injury.

When the oscillator is placed on a vessel or hung overboard from a lightship, a large water-tight diaphragm is attached to the oscillator. This particular type of oscillator was first tested by suspending it in twelve feet of water at the Boston lightship and the signals were heard plainly with a microphone lowered overboard from a tug at Peaked Hill Bar Buoy, thirty-one miles away. Since that time tests have been made with oscillators installed in the fore peak tank of the *Devereux*, a collier of the Metropolitan Coal Company, and also with an oscillator mounted on a diaphragm made part of the hull of the vessel. The signals have been heard upwards of twenty miles from the *Devereux* running at her regular speed of eight knots. Full power has not been employed on any of the tests, and it is more than probable that much longer distances can be obtained in the future.

In addition to the tests already described the oscillator has been temporarily installed on submarine boats, and proved itself of immense value and demonstrated that a flotilla of submarines equipped with oscillators will be able to make a combined attack on an enemy, only one needing to show its periscope in order to direct the others, or all of them can be directed by the mother ship. It therefore makes possible a whole field of submarine maneuvers heretofore out of the question; and perhaps most important, it removes the principal danger these boats have had to face, the risk of being run into.

So much for the apparatus when in use as a sound generator. The signals produced by the oscillator can of course be received by water-immersed microphones of the usual type, but one would perhaps not anticipate the possibility of using the oscillator as a receiver, in view of the fact that the diaphragm is of solid steel, and weighs, with the copper tube and its attachments, considerably over 100 pounds; but the oscillator, like the ordinary electric motor, is also capable of acting as a generator, and on account of its high efficiency as a motor, is a very efficient one.

The same oscillator is therefore used for sending and for receiving, a switch being thrown in one direction when it is desired to telegraph under water, and thrown the other way when it is desired to listen in.

In addition to telegraphing and receiving messages, the

oscillator can also be used for telephoning under water. Sentences have been transmitted at 800 yards and conversation at more than 400 yards, and this was accomplished with the use of an ordinary telephone transmitter and 6 dry cells.

It seems evident, therefore, that with more power much greater distances can be reached. Long distances are not, however, necessary, as even with a distance of one mile it will be readily understood that this method of under-water telephoning will be of great use as a means of communicating between submarines while submerged, and between ships in fog, as the captains of the vessels can talk directly to each other, instead of transmitting and receiving through a telegraph operator.

Some other uses to which the oscillator may be put may be mentioned briefly.

One which will at once suggest itself is the steering of torpedoes by sound under water. The idea of so operating torpedoes is not a new one, and has occurred to a number of inventors, but until the present time no method of accomplishing it has been developed. With this new source of sound, however, the method should be practicable.

Another use is as a means for obtaining soundings. If we take a commutator wheel, with one live segment and two brushes, one connected to the alternating-current generator and the other to the telephone receiver, it will be evident that when the commutator segment makes contact with the brush connected to the generator, a sound will be produced by the oscillator. When the live contact passes away from the brush, the sound will cease. This sound wave will travel outward and on reaching the bottom will be reflected and travel back again to the ship. Meantime, no sound will be heard in the telephone receiver, but if the brush connected to the telephone receiver be shifted in the direction of rotation of the commutator until it makes contact with the live segment of the commutator, at precisely the instant at which the reflected sound wave has come back and impinged on the oscillator diaphragm then a sound will be heard. Since sound travels in water at a velocity of approximately 4000 feet per second, if the distance be 100 feet, the time taken by the sound in traveling from ship to bottom and from bottom to ship will be approximately one-twentieth of a second.

In April, 1914, some tests were made on the U. S. revenue cutter *Miami* to see whether soundings could be taken in the

manner above indicated. As the commutator had not been completed a temporary apparatus with a stop watch was used. The echo from the bottom was plainly heard not only on the oscillator, but in the wardroom and in the hold of the ship without any instruments whatever. The elapsed time corresponded to the depth shown on the chart and the proposed method was proved to be feasible.

The chief object of the tests on the *Miami* was, however, to determine whether a reflection from icebergs could be obtained, and this was proved beyond question. The apparatus used was the same as for taking soundings.

A signal was sent on the oscillator, the echo from the bottom heard, and then the echo from the iceberg came in. To make sure that the second echo was not also from the bottom, the distance from the *Miami* to the iceberg was varied from about 100 yards to 2½ miles. The elapsed time between the signal and the echo from bottom remained the same, but the elapsed time of echo from the iceberg varied with the distance and corresponded very closely to the position of the iceberg determined by the range finder. Moreover it was found that it made no difference whether the face of the iceberg was normal to the path of the sound or not, thus showing that the echo was due not to specular reflection but to diffraction fringes.

When the *Miami* had gone 2½ miles from the iceberg a heavy storm made it necessary to postpone further tests, and continued rough weather made further tests impossible, as the oscillator was not permanently installed but had to be lowered overboard. The echoes at 2½ miles were, however, loud, and there can be no doubt that they would have been heard at greater distances. (See appendix).

To sum up: The oscillator represents an important step forward in the science of navigation. It makes it possible to surround the coasts with a wall of sound so that no ship can get into dangerous waters without warning, to make collisions between ships possible only through negligence. Although no sufficient tests have been made to warrant the statement that icebergs can be detected under all circumstances or that soundings can be taken at full speed, what evidence there is points that way. For naval purposes it provides an auxiliary means of short-distance signaling that is available at all times and that cannot be shot away, and it widens the possibilities of submarine boats to an extent we cannot yet fully grasp.

REPORT OF CAPTAIN J. H. QUINAN OF THE U. S. R. C. *Miami* ON THE ECHO FRINGE METHOD OF DETECTING ICEBERGS AND TAKING CONTINUOUS SOUNDINGS.*

We stopped near the largest berg and by range finder and sextant computed it to be 450 feet long and 130 feet high. Although we had gotten within 150 yards of the perpendicular face of this berg and obtained no echo from the steam whistle, Professor Fessenden and Mr. Blake, representatives of the Submarine Signal Company, obtained satisfactory results with the submarine electric oscillator placed 10 feet below surface, getting distinct echoes from the berg at various distances, from one-half mile to two and one-half miles. These echoes were not only heard through the receivers of the oscillator in the wireless room, but were plainly heard by the officers in the wardroom and engine room storeroom below the water line. Sound is said to travel at the rate of 4400 feet per second under water. The distance of the ship, as shown by the echoes with stop watch, corresponded with the distance of the ship as determined by range finder. On account of the great velocity of sound through water, it was our intention to try the oscillator at a greater distance for even better results, but a thick snowstorm drove us into shelter on the Banks again.

* * * *

On the morning of April 27, anchored in 31 fathoms of water with 75 fathoms of chain in order to make current observations. . . . Professor Fessenden also took advantage of the smooth sea to further experiment with his oscillator in determining by echo the depth of water; the result giving 36 fathoms, which seemed to me very close.

*From the *Hydrographic Office Bulletin* of May 13, 1914.

DISCUSSION ON "SUBMARINE SIGNALING" (BLAKE), PHILADELPHIA, PA., OCTOBER 12, 1914.

W. S. Franklin: When you lower that oscillator into the water, the two diaphragms are working in like phases, are they not?

H. J. W. Fay: Yes. That means that the water on one side is being compressed.

W. S. Franklin: Don't you cover one of those diaphragms completely, and only expose one to the water?

H. J. W. Fay: This diagram doesn't show the water-tight oscillator as it should. This is a form of oscillator that was put inside the ship, not put in the water. A water-tight oscillator has a ring around the base of the pole piece, and the third diaphragm is mounted on that ring, and this rod excites that diaphragm.

W. S. Franklin: If I may explain just what I have in mind—you say that your wave length there would be something like thirty or forty feet. Now we speak of each side of that apparatus as being a center from which waves go out—

H. J. W. Fay: No, only one side.

W. S. Franklin: That is what I wanted to know. Only one side is covered?

H. J. W. Fay: Yes.

Elmer A. Sperry: This seems to me a most ingenious apparatus. Think of the diaphragm that you and I use when we speak into a telephone, a small affair that is about as thick as paper, and then consider the diaphragm that this apparatus works—three-quarters of an inch thick and 24 inches in diameter; and it takes that size of diaphragm to be in tune with the 1000 beats or 500 full oscillations per second to which this instrument is tuned with the alternating current of this frequency. I understand that when this was tried on the *Delaware* it was heard distinctly on the upper deck in a very remote position from where the apparatus was installed. But the most remarkable thing to me is that it can be again used as a receiver. The 8 by 8-in. copper tube, only $\frac{1}{8}$ in. thick, seems a very simple factor to set up a reaction back into the alternating winding, giving evidence of remote sound, especially when in attune with this diaphragm.

G. A. Hoadley: The paper speaks of the most important use of this apparatus on submarines, for submarine signaling from one vessel to another. Has there been any method devised by means of which submarines not belonging to our party can be prevented from receiving the message?

H. J. W. Fay: No, not yet. At a mile's distance, the sound is so loud that it can be heard all over the submarine boat without any receiving apparatus. The point that you mention has been in mind, but it could not be done with vibra-

tions such as are used now. It would be possible with vibrations that are below the range of audibility.

H. A. Hornor: Have any experiments been made upon interference of two signals at a time? Wouldn't that be a cause of confusion of the signals?

H. J. W. Fay: Yes, probably, unless they were widely different in tune. Then the oscillator at 500 might not pick up the oscillator that was tuned to 1000. We have simply worked the oscillator out for that one pitch at the present time, and the greatest number that we have known to be used at any one time has been two. We have not had a third oscillator in any of the tests to break in on the signals.

W. S. Franklin: Professor Webster of Clark University has been working quantitatively on a problem which involves making, among other things, an accurate measurement of the number of watts that are given out as sound by ordinary tuning forks, with and without resonance. Have you any idea as to the actual watts output represented by the sound that is produced? I don't mean watts entering into the receiver, but watts of energy in the sound.

H. J. W. Fay: The nearest I can tell you is that last Saturday we made a test with one oscillator 46 ft. from the other and measured the amount of current received in the alternating winding of the receiving oscillator, and we got 0.025 ampere. The input was 13 amperes at 170 volts on the alternating current and 7½ amperes at 110 volts on the direct-current winding.

George Breed: As I understand the description, the armature oscillates in a direction longitudinal with the bolt. Then, presumably, it must be centered in some way and held clear and free between the magnet poles, and furthermore, if it be free to oscillate, its supports cannot be absolutely rigid.

It would be interesting to know how the armature is held in place, and how much elasticity there is in its supports. I suppose the oscillating system thus formed is so proportioned with respect to mass and elasticity, that its natural frequency of oscillation is about 500 per second.

H. J. W. Fay: The amplitude of movement is 0.01 in. The small diaphragms on the rod support the copper tube.

W. S. Franklin: If the amplitude of this apparatus is known, Professor Webster's formula will enable the actual watts of sound output to be calculated with a very high degree of accuracy.

John B. Taylor (by letter): Before commenting in detail on the paper by Mr. Blake, a few very general (and perhaps obvious) remarks may be in order.

Communications between individuals more or less widely separated may be accomplished only by transfer of matter or energy from one to the other. Exchange of intelligence by moving material things has culminated in the typewritten letter.

The spoken word and the sign exemplify communication

through forms of energy. Here one involves mechanical, the other radiant energy. In the business of travel and transportation by land, as well as by sea, both audible and visible signals are extensively employed, one supplementing the other. Light signals serve fairly well in disclosing location or direction through "straight-line" propagation of the radiant energy and the working characteristics of the receiving instrument, the eye. Non-transparent objects cast shadows, *i.e.*, the radiation does not bend around obstacles, hence rain, snow and especially fog disturb, or prevent entirely, dependence on visual signals. Layers of air of different optical properties may also give rise to mirages or other aberrations.

Sound signals do not readily disclose location or direction. Sharp sound shadows are not noticed with wave lengths of the pitches commonly employed, and the ears are not well adapted nor trained to locate sources of sound with assurance or accuracy. Further difficulties arise on account of reflections from objects giving echoes or interferences which may be misleading, while other sounds and noises, necessary and unnecessary, reduce the sensibility of the ear to feeble sound and distract the attention from the particular sound signal.

The paper under discussion describes a system of marine sound signaling using the water of ocean, river or lake rather than the air as transmitting medium. To do this, more complicated sounding and receiving equipment is needed. Doubtless the water will usually be more homogeneous acoustically than the air. The inhabitants of the water are assumed to be comparatively quiet. There are, however, extraneous sounds which give trouble. Is it right to infer that these are greater than undesired sounds in the air, since no mention of this point is made in the list of five advantages of water over air? (page 1551).

The descriptions of the determination of depth and of iceberg distance by echo and reflection naturally lead one to question the reliability of direction location in the presence of other ships, icebergs, rock ledges, reefs, islands, not to mention shore and bottom.

The greater speed of transmission through water (approximately 4 times) is an advantage from a telegraphic standpoint where sound signaling through air would leave the hearer a full minute behind the sender in 11 or 12 miles. In fact, the 15-sec. interval for water signaling for the same distance may make much confusion. The greater velocity is a disadvantage in depth and distance determinations.

The remarks of the author (page 1554) on compressibility of water and large forces and strength of materials needed to make a sound in water are incomplete without data on the number of kilowatts expended and the excursion of the copper tube with its attachments and diaphragm. A steel rod will readily transmit the sound of a pin scratching or a watch tick-

ing, though the velocity of sound in steel is about 14 times that in air and though steel is much heavier than water, thus indicating far greater rigidity or incompressibility than water.

What is the basis of the author's statement that a telegraphic "dot" must persist ten cycles for its pitch to be recognized? Lord Rayleigh ("Theory of Sound," Vol. II, page 452) cites tests to show that *three* consecutive vibrations determine pitch with considerable accuracy. Tests of Mr. Arthur Farwell (Massachusetts Institute of Technology thesis, 1893, I believe unpublished) using a different method—a telephone receiver—corroborate the figure.

Submarine signaling by the "telegraphic oscillator" may well supplement other signal methods, as none are complete and at all times dependable. Sound signals through air must be retained for the benefit of small craft that cannot have submarine devices. Though a given sound may not always be heard at the same distance, the air is the natural medium for men. The ear, while sensitive to feeble sounds, may be aided, and an increased range may be obtained by the help of apparatus. Probably many cases of alleged erratic transmission of sound are due to mistakes in judging direction. To determine better the direction of the source of sound, an interference device or apparatus indicating phase of sound at two slightly separated points determines the direction from which the sound wave arrives (see U. S. patent No. 939,349).

G. A. Hoadley: One question in connection with this paper is the necessity of a high degree of energy in sending out the sound. A pin scratch on a wire fence can be heard at a long distance, not because the steel or iron wire used is so little compressible, but because of its high elasticity, and it seems to me that in the case of submarine signaling it is a question of higher elasticity of the medium rather than the amount of the compression that is to be used. I am questioning whether it would be possible in any way to apply less energy and still set up the wave motion.

J. L. Woodbridge: How accurately can the direction from which the sound proceeds be determined by the receiving vessel?

H. J. W. Fay: Within a point on the compass, or 11¼ deg., at distances of between two and three miles.

W. S. Franklin: The accuracy of locating directions of sound must depend on the distance apart of the two points at which the sound is received. How far apart are the two receivers when you attempt to locate directions of sound—ten feet, or so?

H. J. W. Fay: The distance between the two sides of the bow of a ship—more than ten feet.

Presented at the 300th Meeting of the American Institute of Electrical Engineers, Philadelphia, Pa., October 12, 1914, under the auspices of the Committee on Use of Electricity in Marine Work.

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ELECTRICAL EQUIPMENT OF THE ARGENTINE BATTLESHIP "MORENO"

BY H. A. HORNOR

ABSTRACT OF PAPER

This paper describes the electrical installation of one of the two Argentine battleships building in this country and now nearing completion. The methods of installation and distribution of energy; the extensive application, far surpassing any vessel so far constructed in this country, and the results secured by departure from present practise; all these are concisely recorded.

Detailed descriptions are given of important and unusual equipments such as steering gear, anchor windlass, searchlights, gyro-compass, etc., etc.

THE MORENO is one of the two super-dreadnoughts building in this country for the Argentine Republic. The general characteristics of the *Moreno* are as follows:

Length over all, 594 ft. (181 meters); displacement, 27,566 tons (28,000 metric tons); draft, 27 ft. 9 in. (8.46 meters); width 98 ft. 0 in. (29.89 meters); main battery, twelve 12-in. (304.8-mm.) breech-loading rifles mounted in six turrets; torpedo defense battery, sixteen 4-in. (101.6-mm.) and twelve 6-in. (152.4-mm.) breech-loading rifles.

It is the purpose of this paper to describe in general the electrical equipment of this vessel. The applications are so numerous and varied that only the unusual equipments have been selected for detailed comment. By reason of the confidential nature necessarily involved in military applications, all reference to such has been omitted. As all installations of this character are divided into three general systems, namely, lighting, power, and signaling, this grouping will be followed.

GENERATING PLANT

Power for all purposes is supplied by four 375-kw. turbo-generators of the horizontal type. Two of these machines are located forward and two aft on the lower platform deck below armor. Adjacent to each dynamo room is a distribution room

in which is located a main distribution switchboard for the control of the two units and the supply circuits. On the gun deck is a third dynamo room containing two Diesel oil-engine-driven generators of 75 kw. capacity for harbor use when fires are drawn.

The 375-kw., 230-volt, 1500-rev. per min. turbo-generators are of standard marine design capable of operating at a steam pressure of 220 lb. per sq. in. (15.4 kg. per sq. cm.), condensing at a normal vacuum of 28 in. (71.1 cm.), and also non-condensing with 5 lb. (2.27 kg.) back pressure. The turbine is of the well-known Curtis horizontal, two-stage type, fitted with automatic valve gear, inertia governor, and an emergency valve for automatically closing when the speed exceeds 10 per cent of normal. Forced lubrication is provided for the main bearings, and the oil is cooled by water circulation. The generator is a compound-wound, direct-current, commutating-pole type, mounted on the same bedplate and directly coupled to the turbine. The magnet frame is circular in form and divided horizontally. The generator is capable of standing a 33⅓ per cent overload for two hours and 50 per cent overload for five minutes.

The Diesel oil-engine-driven sets are rated at 75 kw., 375 rev. per min., 230 volts. The generator is directly connected to the oil engine but not mounted on the same bedplate. The generators are designed in a similar manner and are capable of functioning in the same way as the main generators above described. The Diesel oil engine is guaranteed to develop 120 b.h.p. normally and also 180 b.h.p. overload. The engine is vertical, four-cycle, single-acting, and is provided with four power cylinders and one air-compressor. The engine is started by means of compressed air at about 650 lb. per sq. in. (45.5 kg. per sq. cm.) obtained from storage tanks. During the starting of the engine the cooling water is gradually started and will be in full flow when normal ignition has been established. The plunger for the fuel oil pump is operated by an eccentric attached to the vertical shaft of the valve gear drive. An auxiliary cooling water pump and fuel oil pump are also provided. These auxiliaries are electrically driven, the former by a 2.7-h.p. motor and the latter by a 1.75-h.p. motor. The fuel oil used may be fairly heavy, even heavier than 20 deg. Beaumé at 60 degrees fahr., so long as it flows readily and can be handled by the fuel oil pump. The heat value of the oil should not be less than 18,500 B.t.u. per pound (4662 kg-cal.).

Installation and Distribution

Current is carried to all the various systems on a two-wire metallic system, by means of rubber-covered (44 per cent pure Para) lead-sheathed, steel-armored conductors. These cables are clipped singly, or in groups, to the ship's structure or clipped to special sheet steel pans supported from beam to beam or fastened to the plating. Water-tight fittings are provided wherever the cables terminate and when passing through water-tight bulkheads. Twin conductors are employed from 3256 cir. mils up to 30,856 cir. mils, and beyond this, single conductors up to 373,737 cir. mils. All the conductors in this installation are stranded, lead-covered, steel-armored, with the exception of the flexible leads in the turret trunks and special brass-covered wire and three-conductor rubber-insulated wires, called by the German trade name "Kuhlo," used for branch leads in the officers' quarters and staterooms.

Besides the two main distribution switchboards located adjacent to the two dynamo rooms, there are two auxiliary distribution boards located one forward and one aft; a control board for the oil engine generators; and a combined distribution and control board for the searchlight balancer sets. These boards are all interconnected so that the supply will always be available. The interconnecting circuit breakers are fitted with interlocking devices and reverse-power relays so that by no possibility will the generators in one room be thrown in parallel with those in another room. The distribution switchboards are designed with separate busbars for positive lighting and positive power and a common negative. It is possible, therefore, to divide the load in various ways between the different dynamo rooms. To facilitate this, indicating voltmeters and ammeters are connected in the local and remote circuits and a diagram of the busbar connections is painted in grooves on the front face of the oil-finished slate panels.

Lighting System

The vessel is provided with approximately 3000 fixtures. The design is similar to the usual water-tight vapor-proof globe type used in marine work. The screw-base lamp socket is, however, made solid instead of a spring, a composition-insulated base provided instead of porcelain and the globe is flanged and held in place by the guard instead of being screwed into the base. In the magazines and shell rooms, specially guarded fixtures con-

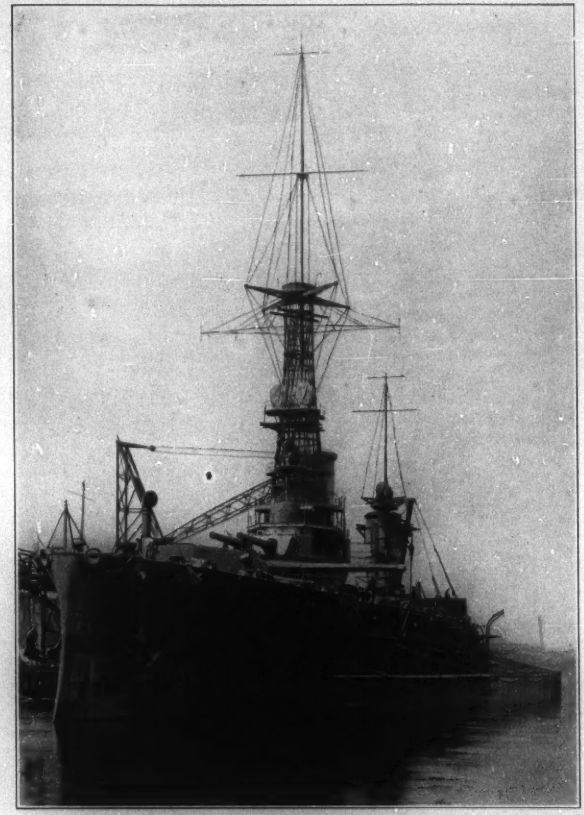
taining two lamp sockets are installed. The lamps in these fixtures are connected to different circuits so that the failure of light in these compartments may be averted. Both carbon and tungsten incandescent lamps are furnished; the former in sizes of 35 watts and 60 watts, clear; the latter in sizes of 32 watts, clear, frosted and tubular. A special fixture containing a 250-watt tungsten lamp and provided with a reflector is arranged for portable connection in the engine, boiler, and dynamo compartments. This same type of fixture is also employed for coaling booms, propeller booms, and gangway lighting.

Life tests of the 220-volt tungsten incandescent lamps showed as high as 98 to 101 per cent of the initial c.p. after 1162 to 972 hours burning. The spherical reduction factor for the tubular lamp was 0.96 and for the pear-shaped bulb (s-19) was 0.914.

The 38 lighting feeders are divided into three circuits; one for general illumination under cruising conditions, one for white battle purposes, and one for blue battle purposes. In this latter circuit the globes are of a deep blue color, making the light invisible at a short distance. The distribution of the small lighting units has been made with due regard for cross circuits so that no general spaces of the vessel may be put in darkness by the blowing of a fuse or any other failure of an individual circuit. The distribution of these lights was based on the number of candle power per cubic foot of space to be lighted; thus in the Admiral's quarters a maximum of 0.08 c.p. per cubic foot was required and in the storerooms a minimum of 0.01 c.p. per cubic foot. Each officer's stateroom of ordinary size is provided with one fixed light, one portable light, and an outlet for a 12-inch portable electric fan.

As shown in the diagram (Fig. 2) the feeders are led from the main distribution switchboard to approximately their center of distribution. Mains are then branched from the feeder, and terminate in fused distributing panels of water-tight construction. From these panels branches are led off to the individual lights. Not more than four lights (one ampere) are allowed to depend upon the same fuse. The branch leads are all of 1.6-mm. (3250-cir. mil) twin conductor.

For night battle purposes the vessel is equipped with 12 motor-operated, remote-electrically-controlled 110-cm. (43.3-in.) searchlights and one portable signaling projector of 35 cm. (13.77 in.). As these projectors operate more satisfactorily when supplied with 110 volts, it was considered advisable to



[HORNOR]

FIG. 1—*Moreno* AT THE YARDS OF HER BUILDERS, AUGUST 19, 1914

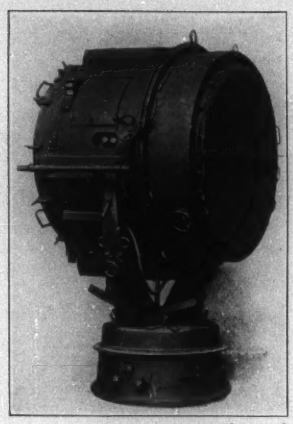


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FIG. 3—ELECTRICALLY CONTROLLED SEARCHLIGHT

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FIG. 4—SEARCHLIGHT LAMP MECHANISM

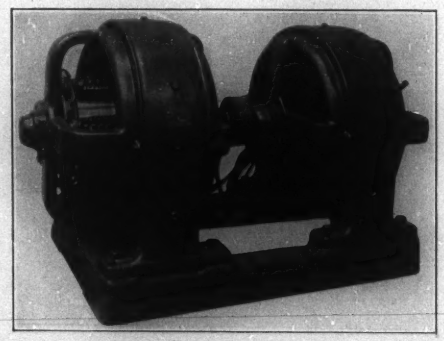

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FIG. 8—SEARCHLIGHT BALANCER SET

transform the 220-volt supply circuit through special balancer sets. Two such machines are installed in the vicinity of the oil engine dynamo room, wherein are located the control switchboard for them and the distribution board for the search-light feeders. Each balancer set is rated at 70 kw., 1000 rev. per min., 110 to 220 volts, the full load current on the neutral being 637 amperes. They are compound-wound, and the series and shunt coils are connected so that they act accumulatively on the generator and differentially on the motor. The series and shunt coils in one frame are connected across the armature of the other frame for the purpose of producing constant voltage at each end. The

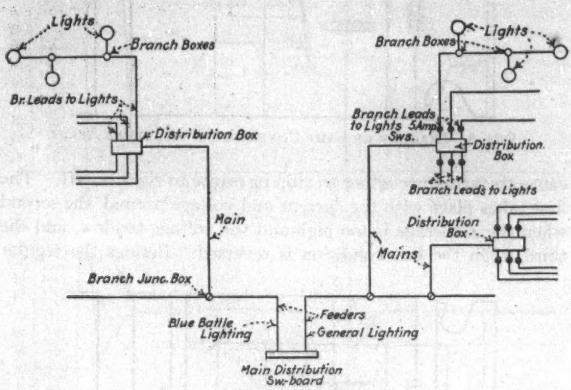

FIG. 2—DISTRIBUTION DIAGRAM

sets will maintain a difference of potential not in excess of seven volts under any conditions of load with an impressed e.m.f. of 220 volts. Either end of these sets operates as a motor or generator as may be demanded by the load.

Only a brief description can be given of the searchlights proper. Fig. 4 shows the lamp mechanism. Fig. 5 is a wiring diagram when the carbons are apart, Fig. 6 the same with the carbons together, and Fig. 7 gives curves illustrating the time saved by the employment of a shunt motor for automatically adjusting the carbons in preference to a compound-wound motor. The twelve 110-cm. (43.3-in.) searchlights are similar in every respect except that one projector is equipped with a remote-electrically-

controlled signaling shutter. The lamp mechanism consists of a small electric motor which functions through gearing and so moves the carbons. The field and armature of the motor are controlled by a differential relay and two auxiliary relays which

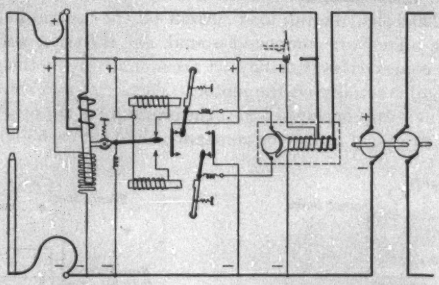

FIG. 5—DIAGRAM OF LAMP CONNECTIONS—CARBONS APART

cause the armature either to stop or rotate to right or left. The first takes place with the current and voltage normal, the second when the amperage is too high and the voltage too low, and the third when the last condition is reversed. Besides the regular

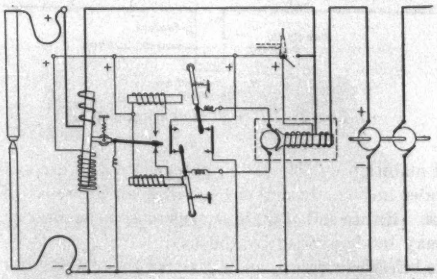

FIG. 6—DIAGRAM OF LAMP CONNECTIONS—CARBONS TOUCHING

field winding there is an additional winding on the motor field to carry the full lamp current. This produces a strong field when the voltage across the arc falls below normal and furnishes a dynamic braking effect for retarding the movement of the motor armature. For signaling purposes the searchlights are equipped

with iris shutters similar to camera shutters. These are all manually operated, except one, in which latter case a venetian blind shutter, remotely controlled, is also provided. The optical arrangements are such as to provide rapid means for changing over from a dispersed to a closed beam of light. This is accomplished by means of a double disperser, consisting of two parallel systems of plano-convex cylindrical lenses, which may at will be drawn together or separated. A sighting telescope at-

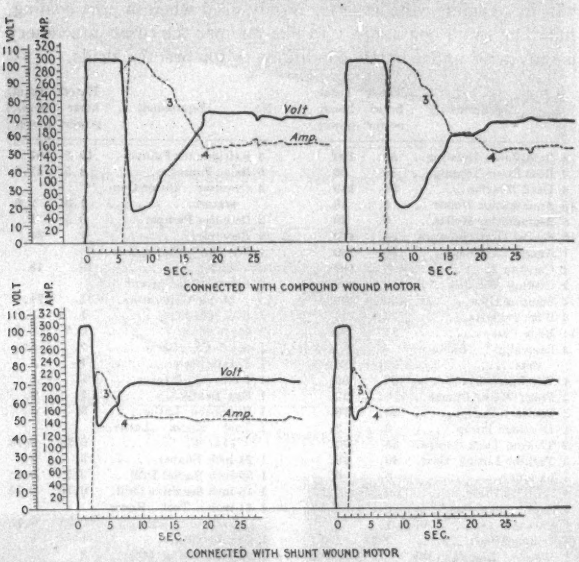

FIG. 7—TIME DIAGRAMS OF SEARCHLIGHT LAMP MOTORS

tached to the side of the drum; a complete lamp telegraph indicating the positions of the searchlight at the controller; and a set of electrical instruments, consisting of a voltmeter and ammeter, are furnished with each searchlight. A complete horizontal cycle of the searchlight may be accomplished either in 28 seconds or approximately 15 minutes by means of the electric remote control. This control may be detached and the mechanism operated locally by hand.

Power System

The following list shows the extensive applications of the electric power and gives the rated load for each equipment. It should be borne in mind that these numerous equipments have their special uses and are brought into action in general upon different occasions. Such systems as the ventilation system, sanitary pumps, etc., etc., are continuously in service; but on the other hand the deck machinery such as boat booms, deck winches, coaling winches, etc., is only used when in port coaling, handling small boats, etc. In like manner the turret machinery is only used under battle conditions or for practise drills.

No.	Equipment	Rated horse power	Total horse power
2	Boat Boom Hoisting..	50.	100.
2	Boat Boom Topping ..	30.	60.
4	Deck Winches.... ...	35.	140.
16	Ammunition Hoists...	3.	48.
6	Ammunition Hoists...	5.	30.
12	Forced Draft Blowers.	35.	420.
1	Anchor Windlass.....	100.	100.
1	Capstan	100.	100.
2	Coaling Winches.....	150.	300.
1	Steering Gear.....	150.	150.
3	Bilge Pumps..... ...	70.	210.
14	Bilge Pumps.....	35.	490.
2	Searchlight Balancer Sets.....	93.	186.
1	Fire Pump.....	60.	60.
2	Fresh Water Pumps..	6.	12.
2	Sanitary Pumps.. ...	35.	70.
1	Drainage Pump.....	3.	3.
2	Thermo Tank Pumps.	35.	70.
3	Turbine Lifting Gear.	30.	90.
1	Laundry.....	6.	6.
1	Printing Press...	0.25	0.25
3	Speed Signal Balls....	0.5	1.5
1	Cake Mixer....	1.	1.
1	Dough Mixer.....	2.5	2.5
1	Diesel Engine Oil Pump.....	1.75	1.75
1	Diesel Engine Cooling Water Pump..	2.7	2.7
12	Turret Turning.....	25.	300.
12	Gun Elevating...	15.	180.
13	Turret Hoists.....	7.5	97.5
5	Turret Hoists.....	12.	60.
1	Dryer Room.....	1.	1.
1	Roentgen Ray Equipment.....	5.	5.
1	Vacuum Cleaner.. ...	0.33	0.33
1	Electro - Mechanical Hammer..	5.	5.
2	Torpedo Air Compressors.....	90.	180.
5	Refrigerator Pumps...	19.5	97.5
5	Brine Pumps.....	3.5	17.5
2	Ozonizer Motor-Generators.....	1.3	2.6
2	Ozonizer Pumps.....	0.5	1.
9	Elevators.....	4.	36.
1	Wireless Motor-Generator..	18.	18.
2	Alternating-Current Motor-Generators..	37.	74.
1	Dish Washer.....	1.	1.
1	Meat Slicer.....	0.5	0.5
1	Meat Chopper.....	1.	1.
1	Potato Peeler...	1.	1.
1	Ice Cream Freezer....	1.	1.
1	Egg Beater.....	2.	2.
1	Extension Lathe.....	3.	3.
1	Tool Room Lathe, 14-inch.....	0.75	0.75
1	24-inch Shaper.....	3.	3.
1	30-inch Radial Drill...	2.5	2.5
1	16-inch Sensitive Drill.	0.75	0.75
1	14-inch Tool Room Lathe.....	0.75	0.75
1	Grindstone.....	1	1
1	46-inch Boring Mill...	3	3
1	Cutter and Grinder...	1	1
1	Tool Room Lathe 14-inch	0.75	0.75
1	Sensitive Drill 16-inch.	0.75	0.75
1	Lathe for Armorer's Workshop.....	0.75	0.75
1	Shaper for Armorer's Workshop.....	2.	2.
1	Sensitive Drill for Armorer's Workshop..	0.75	0.75
1	Forge Blower....	0.75	0.75
1	Foundry Blower.....	5.	5.
1	Athletic Horse.....	2.	2.
1	Moving Picture Machine..	17.6	17.6

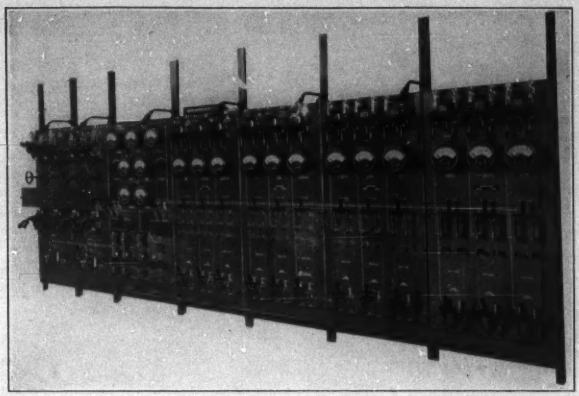

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FIG. 9—SEARCHLIGHT DISTRIBUTION SWITCHBOARD

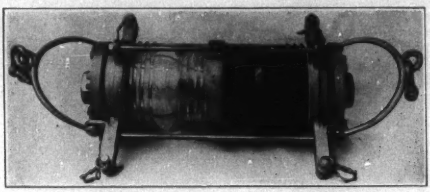

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FIG. 9a—NIGHT SIGNAL SET LANTERN

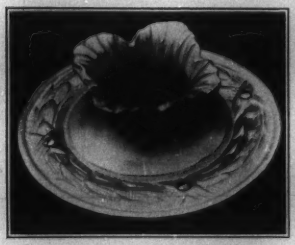

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FIG. 9b—SILVER FIXTURE—ADMIRAL'S QUARTERS

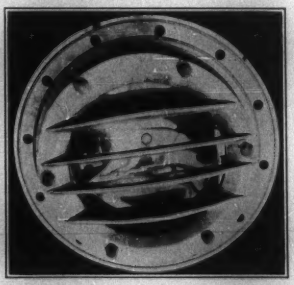

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FIG. 9c—BULKHEAD BUNKER FIXTURE

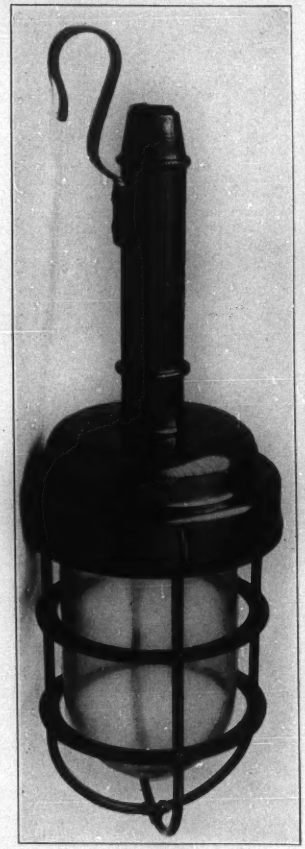

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FIG. 9d—WATER-TIGHT PORTABLE LAMP

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FIG. 9e—BRACKET FIXTURE

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FIG. 9f—DESK PORTABLE

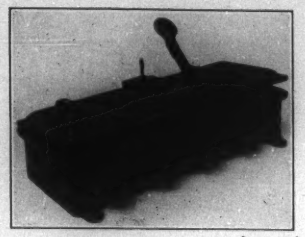

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FIG. 9g—SELF-CLOSING DISTRIBUTION BOX

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FIG. 9j—FEEDER JUNCTION BOX, 4-WAY

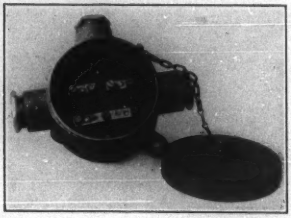

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FIG. 9h—WATER-TIGHT BRANCH JUNCTION BOX—THREE-WAY

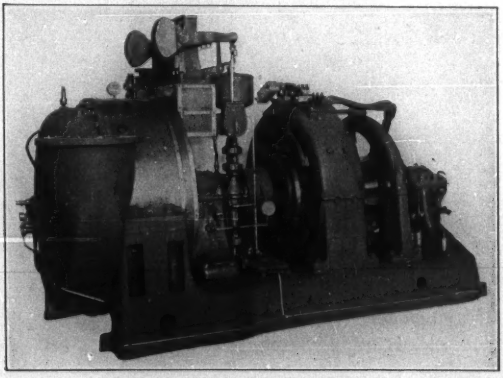
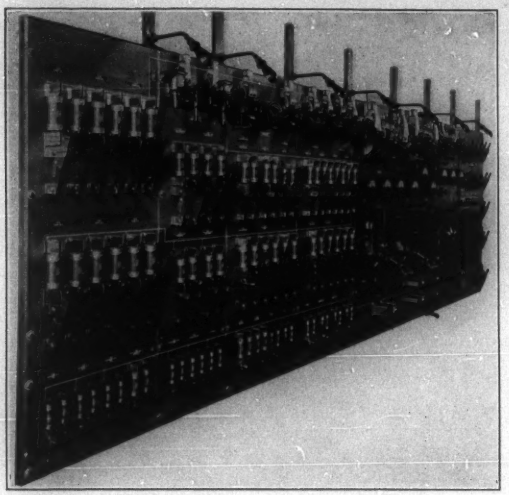
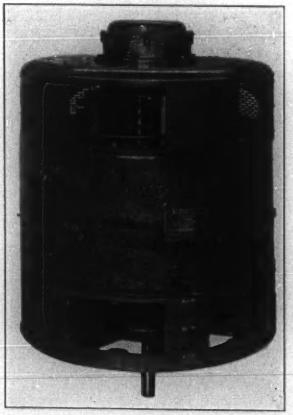


FIG. 12—375-KW. GENERATOR [HORNOR]



[HORNOR]

FIG. 13—MAIN DISTRIBUTION SWITCHBOARD



[HORNOR]

FIG. 14—BILGE PUMP MOTOR

No.	Equipment	Rated horse power	Total horse power
9	600-cu. ft. Ventilation Fans	4.	36.
9	1600 cu. ft. Ventilation Fans	1.	9.
1	1600 cu. ft. Ventilation Fan	2.	2.
6	2500 cu. ft. Ventilation Fans	1.5	9.
24	2500 cu. ft. Ventilation Fans	2.75	66.
3	2500 cu. ft. Ventilation Fans	3.5	10.5
4	5000 cu. ft. Ventilation Fans	3.25	13.
6	5000 cu. ft. Ventilation Fans	6.	36.
2	5000 cu. ft. Ventilation Fans	6.75	13.5
7	6000 cu. ft. Ventilation Fans	3.75	26.25
5	6000 cu. ft. Ventilation Fans	7.	35.
2	8000 cu. ft. Ventilation Fans	5.	10.
6	8000 cu. ft. Ventilation Fans	9.	54.
2	10,000 cu. ft. Ventilation Fans	6.25	12.5
3	12,000 cu. ft. Ventilation Fans	7.5	22.5
2	15,000 cu. ft. Ventilation Fans	10.	20.

As shown in the cable scheme for power distribution (Figs. 10 and 11) the feeders from the main distribution switchboards in some cases are led directly to the motor starting panel, in others they are branched into mains and in others they are led to special distribution panels. This latter is so in the case of the four-in. (101.6-mm.) and six-in. (152.4-mm.) ammunition hoists, the searchlights, and the 12-in. (304.8-mm.) turrets. The turret distribution panel is located on the revolving part of the turret and is encased in a water-tight steel box.

As shown by the illustrations, a variety of motor types is used, viz: open, semi-enclosed, fully enclosed, and enclosed-ventilated. The small motors up to 10 h.p. are regulated by simple starting and field control panels. Above 10 h.p.-drum controllers are employed. On the very large equipments performing special service and requiring 50 to 150 h.p., contactor control with dynamic braking is provided.

Steering Gear

The electrical equipment is designed as an auxiliary to the steam steering engine, operates through the same telemotor gear on a "follow-up" system, and furnishes only sufficient power to carry the rudder from hard-over to hard-over in 40 seconds, which is half the time requirement of the steam gear. The motor is of the commutating pole, open type, compound-wound, rated at 150 h.p., 400 to 600 rev. per min., 220 volts. The controlling appliances comprise a master controller and limit switch mounted in one case, a contactor panel and the necessary field and armature rheostats operated by the same. In the

master controller are two cylinders provided with rings; these make electrical contact with plungers; one of these cylinders is for the controller, the other for the limit switch. Both cylinders turn freely on their supporting shafts. The controller cylinder operates through a connecting rod from the operating shaft of the steering gear. The limit switch cylinder operates through a sprocket chain from the main steering gear shaft. The differential gear, or "follow-up" device, is located between the two cylinders and is designed to turn the controller cylinder off by motion of the main shaft of the steering gear which turns the limit switch.

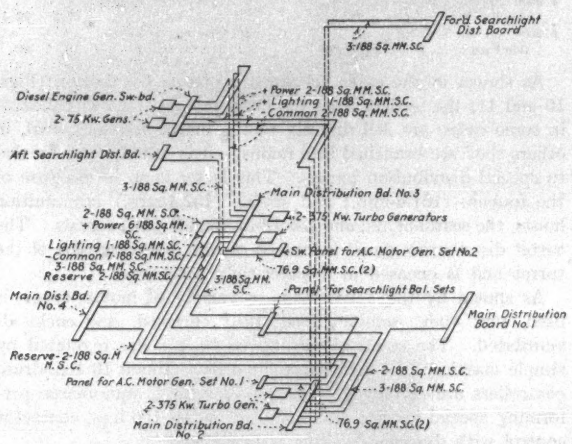


FIG. 10—DIAGRAM OF POWER DISTRIBUTION

The latter strengthens the field of the motor when the rudder is displaced more than 10 deg. from the midship position. The mechanical connections are such that the motor will stop when the rudder has reached the angle for which the steering wheel has been turned. The motor field cannot be weakened until all of the accelerating contactors have closed, after which the controller will maintain full field until it has been turned through an angle corresponding to 3 deg. movement of the rudder from starting position, and intermediate field from 3 deg. to 5 deg., after which the motor will run at weak field until the rudder has

reached 10 degrees from the midship position. Mounted upon the contactor panel are 10 armature contactors, two field contactors, one disk brake contactor, two counter e.m.f. contactors, an overload relay, a double-pole, fused, control switch, and a single-pole testing switch. The overload relay controls four of the five accelerating circuits whereby they operate, resistance is introduced into the armature circuit, and the field rheostat short-circuited so that the motor is protected against continued overload without being actually stopped. In this manner accidentally losing control of the rudder cannot occur. The limit switch is arranged to stop the motor at the 35-deg. position of the rudder. Dynamic braking is provided in connection with the electro-

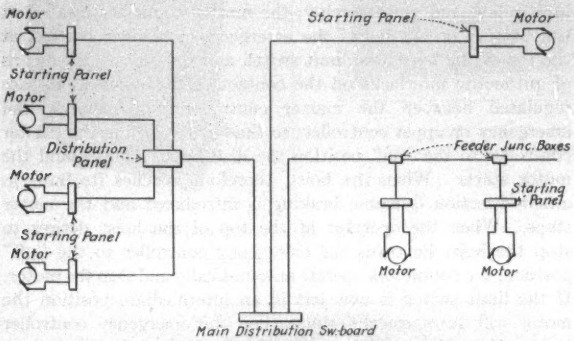


FIG. 11—CABLE SCHEME FOR POWER DISTRIBUTION

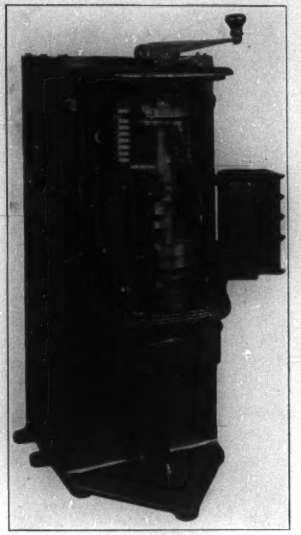
mechanical disk brake in order to provide prompt stopping. The rudder can be turned at slow speed throughout its travel, provided the steering wheel is turned slowly, thereby permitting the motor to turn the controller cylinder backward as fast as it is turned forward by the steering wheel. This may be accomplished while the controller cylinder moves back and forth between limits corresponding to 2.25 degrees motion of the rudder, as the motor will start with a motion of cylinder equivalent to 0.75 deg. movement of the rudder and the field will be weakened with 3 deg. similar motion.

TURRET HOISTS

The turret turning gear and gun elevating gear are operated by constant-speed motors, and speed variations are accomplished

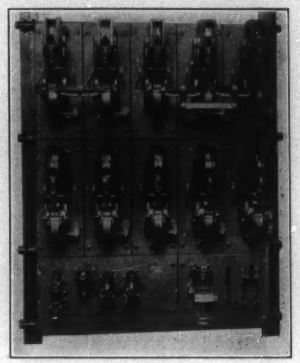
by mechanical means. Ventilation blowers in the turrets are similar to the regular hull ventilation fans, except for increased pressure. The independent hoists complete the electric power equipment of the turrets. The main ammunition hoists are operated by hydraulic power and the electric hoists are provided as an auxiliary. Two upper hoists are fitted in each of the six turrets. These are operated by 7.5-h.p. motors. One lower hoist is fitted in each turret. One of these is operated by a 7.5-h.p. motor and the others by 12-h.p. motors. As these equipments are generally similar in their operation, only the 12-h.p. lower hoist will be described.

The apparatus consists of: a contactor panel upon which are mounted the accelerating contactors, overload relay, current-limit relay, and voltage relay; the master controller located at the bottom of the hoist; the emergency controller located at the top of the hoist; the limit switch and rheostats. By means of automatic interlocks on the contactors the connections are regulated between the master controller, limit switch and emergency or upper controller; so that upon turning the master controller to the "on" position the disk brake releases and the motor starts. When the hoist, therefore, reaches its limit in either direction dynamic braking is introduced and the motor stops. When the operator at the top of the hoist desires to stop the hoist he turns the emergency controller to the "off" position, the contactors operate automatically and stop the motor. If the limit switch is now left in an intermediate position the motor will automatically start when the emergency controller is turned to the "on" position. If the limit switch has been turned to the "off" position by the hoist then the motor will not start until the master, or lower, controller is turned to the first controller notch. In case of overload, the overload relay through the interlocks will open the contactors automatically and stop the motor. The hoist cannot be started again until the operator returns the master controller to the "off" position, which permits the plunger of the overload relay to drop. It is necessary to unlock the reversing cylinder of the master controller mechanically in order to use the hoist for lowering. The connections for this operation are so arranged that the accelerating contactors and current-limit relays are inoperative and suitable resistance introduced in parallel with the armature and a large current capacity resistance connected in series with the armature and starting resistance; by reason of which the



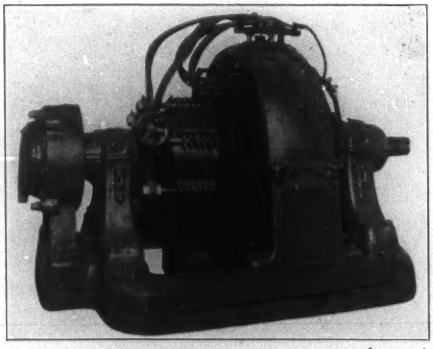
[HORNOR]

FIG. 15—BILGE PUMP MOTOR CONTROLLER



[HORNOR]

FIG. 17—CONTACTOR PANEL FOR STEERING GEAR MOTOR



[HORNOR]

FIG. 16—STEERING GEAR MOTOR

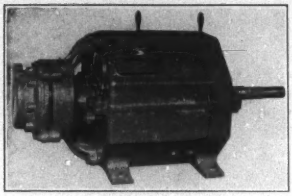


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FIG. 18—BOAT BOOM MOTOR

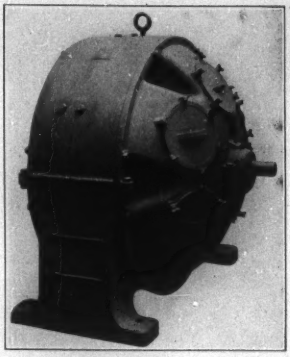

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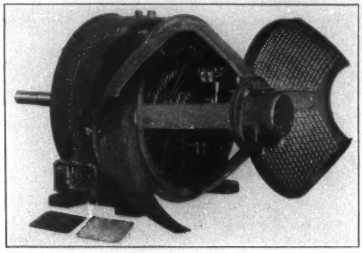
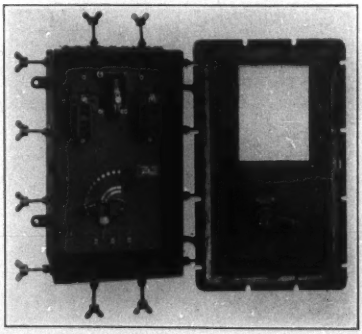
FIG. 19—FORCED DRAFT FAN MOTOR



[HORNOR]

FIG. 20—HULL VENTILATION FAN MOTOR



[HORNOR]

FIG. 21—CONTROL PANEL FOR HULL VENTILATION MOTOR

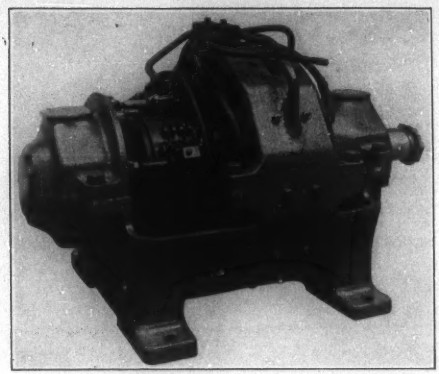


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FIG. 22—COALING WINCH MOTOR

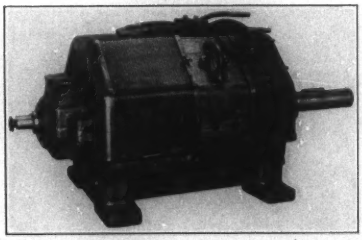

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FIG. 23—ANCHOR WINDLASS MOTOR

[HORNOR]

FIG. 26—LOUD SPEAKING TELEPHONE, WATER-TIGHT

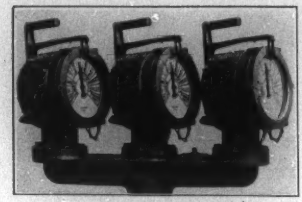

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FIG. 27—ELECTRIC ENGINE TELEGRAPH TRANSMITTER

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FIG. 28—ELECTRIC ENGINE TELEGRAPH RECEIVER

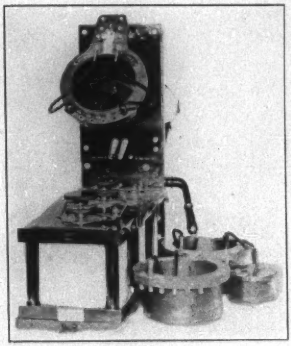

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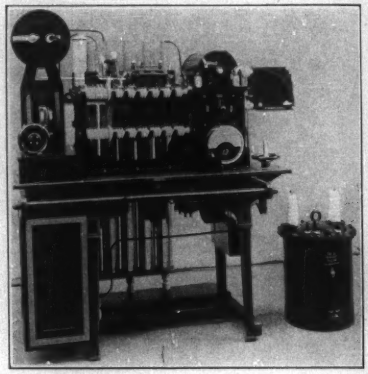
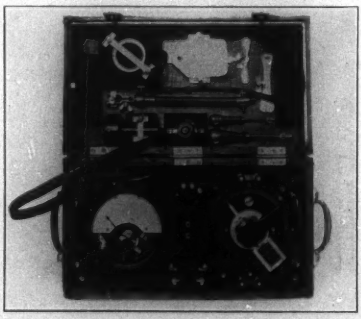
FIG. 31—WIRELESS TELEGRAPH RECEIVER



[HORNOR]

FIG. 31A—WIRELESS TELEGRAPH TRANSMITTER



[HORNOR]

FIG. 32—WIRELESS TELEGRAPH WAVE METER

hoist will lower slowly. Other functions lowering, are similar to those of hoisting.

Anchor Windlass Equipment

The electrical apparatus acts only as an auxiliary to the steam windlass and is designed to function at half the normal load of the steam gear. The outfit comprises a 100-h.p., 475-rev. per min., compound-wound, commutating-field motor of the open type which is equipped with a disk brake; two water-tight, drum-type, reversing master controllers, one mounted in the windlass room and one mounted on the weather deck; a contactor panel containing the accelerating contactors, a step-back relay, overload relay, a double-pole, single-throw disconnecting switch with field discharge clips, a small single-throw testing switch, and a low voltage relay. The control is semi-automatic, *i. e.*, the first three speeds are controlled by the master controller but beyond that the current-limit relays on the contactors will prevent them from closing until the current in each preceding one has been reduced to a predetermined amount, regardless of the position of the controller cylinder. The setback relay will open the contactors in case the load should be increased beyond that for which the set-back relay has been set, and it will introduce all of the starting rheostat except two sections, thereby reducing the current to about 25 per cent overload on the motor. The overload relay will be set considerably higher than the set-back relay, thus protecting the motor in case of excessive overloads. The overload relay is reset by bringing the controller to the "off" position. The armature and commutating field coils are permanently connected and consequently are reversed together. The low voltage relay prevents the equipment from starting automatically after failure of current, requiring the controller to be brought back to the "off" position, whereupon the circuit will be re-established.

Roentgen Ray Outfit

This equipment is arranged for supply from a 220-volt d-c. circuit. The following apparatus of German manufacture is furnished:

An induction coil with adjustable spark gage and three primary windings. The length of spark gap is 16 inches (40 cm.).

Two Gundelach X-ray tubes.

Two Burger-Central X-ray tubes with curved anticathode, air-cooled.

Two Bauer-Delta X-ray tubes with softening adjustment.

One three-part Wehnelt interrupter with one thin and two thick platinum electrodes.

One control switch panel.

The apparatus is located in the operating room adjacent to the sick bay. It is of interest because of the originality of the application.

Moving Picture Machine

Like the X-ray outfit the installation of a cameragraph on a man-of-war is unusual. The outfit represents the very latest design of such machines and is of American manufacture. The apparatus is supplied by a 220-volt circuit and the films are rotated by an adjustable speed, 220-volt, d-c. motor. All the safety attachments required by the underwriters and those automatic devices necessary for smooth performance are provided. The apparatus is portable.

Signaling Systems

The third division of the electrical equipment is classified under the head of Interior Communication Systems, although a few of these are solely for exterior use. They constitute the means for the transmission of intelligence throughout the vessel and are responsible for its behavior when a component part of a military squadron.

The systems comprising this division are given in the following list and a few of the more important and unusual applications will be briefly described.

Call Bells.
Reply Signals for Mechanical Telegraphs.
Fire Alarm.
Electric Clock.
Shaft Revolution and Direction Indicators.
Electric Log Indicator.
Fuel Oil Indicator.
Ammunition Hoist Indicators.
Gun Firing.
Engine Revolution Order Telegraph.
Helm Angle and Steering Telegraph.
Engine Order Telegraph.
Fire Room Telegraph.
Turret Salvo.
Torpedo Defense Salvo.
Anchor Handling.
Coal Bunker Alarm.
Boiler Firing.
Boat Hour Gong.
Day Battle Salvo.
General Alarm.
Cease Firing.
Torpedo Firing.
General Telephone.
Captain's Telephone.
Fire and Engine Room Telephone.

Turret Telephone.
Fire Control Telephone.
12-in. (304.8-mm.) Fire Control Telegraph.
6-in. (152.4-mm.) Fire Control Telegraph.
Turret Danger Zone.
Turret Tell-Tale.
Azimuth.
Course Telegraph.
Gyroscopic Compass.
Pyrometer.
Anemometer.
Electric Whistle.
Wireless Telegraph.

These systems are supplied with power from two stations on the vessel, the forward interior communication room and the

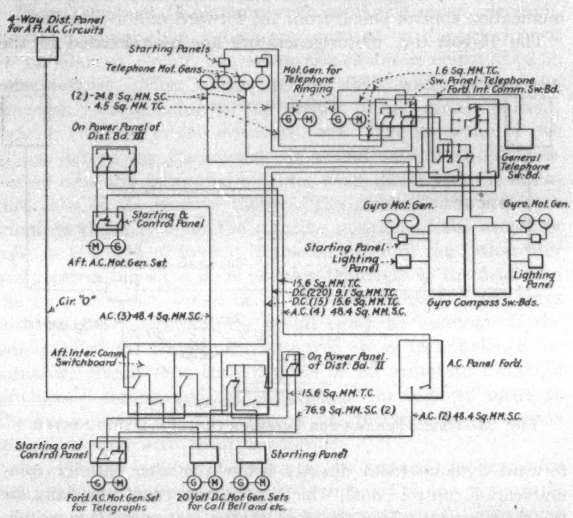


FIG. 24—DIAGRAM OF INTERIOR COMMUNICATION DISTRIBUTION

forward dynamo room. There are two central signaling stations, one forward on the upper platform deck below armor and the other on the gun deck aft. The vessel is further provided with two conning towers, one forward and one aft; two observation towers; and several gun control stations.

A number of these equipments operate on 220 volts direct current, supplied in duplicate from the forward and after main distribution switchboards. However, certain of the telegraph systems require 120 volts alternating current; others, such as the

telephone system, clock system, call bell system, require 15 volts direct current; and the fire control telephone system requires 35 volts direct current. These transformations are accomplished by means of small motor-generators, usually supplied in duplicate. The a-c. motor-generators, which are rated at 18 kw. single-phase, 50-cycle, 120 volts, being of rather large size, are located one in each dynamo room. The a-c. control panel is located in one of the compartments constituting the forward central station. Supply to this panel is brought directly from the control panel of the after motor-generator set and, *via* the after interior communication control panel, from the forward motor-generator.

The 15-volt d-c. motor-generators are both located in the

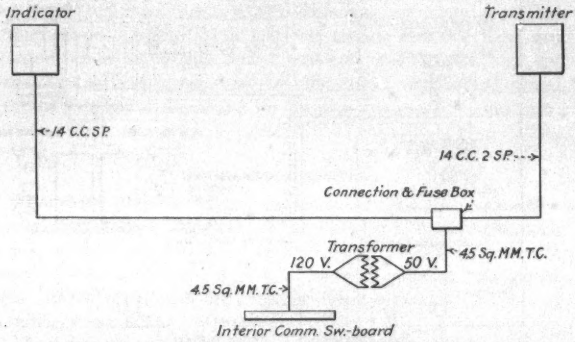


FIG. 25—CABLE SCHEME FOR INTERIOR COMMUNICATION SYSTEM

forward dynamo room directly below the after interior communication control panel, which contains a panel especially for this distribution. Thus the after interior communication switchboard contains three panels; one for the distribution of 220-volt d-c. circuits, one for the 15-volt d-c. circuits, and one for the 120-volt a-c. circuits. The forward interior communication switchboard contains two panels, one distributing 220 volts d-c. and the other 35 volts d-c. This switchboard receives energy from the two 35-volt d-c. motor-generators for the fire control telephone system and the two ringing motor-generators for the general telephone system. It also supplies 220-volt direct current to the two motor-generators for the gyroscopic compass system. The 220-volt busbars are energized directly

from the after main distribution switchboard, and also from the forward main distribution switchboard *via* the after interior communication switchboard. Every possible precaution has been taken to avert any failure of operation due to lack of supply or interruption of service. It is interesting to note that a diagram of the busbar connections is cut into the face of all switchboards and these grooves filled in with colored paint.

Telegraph Systems

There are about 16 systems, such as engine order telegraph, course telegraph, etc., which are operated on the principle of an unbalanced circuit, *i.e.*, when the circuit is undisturbed no current flows. Thus a constant a-c. field, which changes its direction corresponding to the periods of the exciter current, induces currents in the armature coils. The armature of one motor—let us say transmitter—is wound with three interconnected coils and connected by three wires directly to the armature coils of the receiver motor. The power in the armature windings depends upon the rotative position of the armature coils in the field of force. If the armature of the transmitter and receiver have the same position relatively to the field then the induced e.m.f. would be of the same value and the wires between the two armatures would carry no current. If the armature of the transmitter is moved so as to unbalance the armature circuit then current flows in the armature windings, produces a torque, and the armature of the receiver turns to the same position. When this occurs the equalizing currents disappear, and with them the torque.

Any desired number of orders can be arranged for transmission, and any number of receivers connected to the transmitter without increasing the number of connecting wires. Five wires are needed for a simple circuit, two for the field and three for the armatures. For repeating instruments two sets of motors are employed. The transmitter motor is usually larger than the receiver motor, due to the fact that it often operates a number of receivers. Energy is delivered to this apparatus from a 120-volt a-c., single-phase, 50-cycle motor-generator, *via* a step-down transformer, which lowers the potential to 50 volts.

These instruments have a large and varied use, as shown in the above list; sending orders from the bridge to the engine room, indicating the position of the rudder direct from the rudder stock to the navigator, giving orders for a change in course of

the vessel, transmitting emergency orders from the bridge or conning tower when the regular steering gear is deranged, ordering small changes in speed when in squadron maneuvers, furnishing signals from the gun-firing station to each and every gun, and many other purposes too numerous to record.

Pyrometers

There are six boiler rooms on the vessel from each of which are led three uptakes to the two smoke-stacks. Each uptake is provided with a base metal thermocouple pyrometer. Nine of these eighteen couples indicate at two stations, one in the forward boiler room hatch, and one in the after boiler room hatch. The indicators are of the low-resistance type mounted in special water-tight cases and provided with a nine-point switch for the purpose of reading each uptake temperature. The thermocouples are formed of a nickel alloy wire and capable of constantly measuring a temperature of 1800 deg. fahr. and intermittently up to 2000 deg. fahr. The head of the couple is specially arranged for mechanical protection and water-tightness.

Anemometer

This is an unusual equipment for battleships. The apparatus consists of a transmitter comprising a pivoted rotative vane carrying at one end a fan. The vane in orientation and the fan shaft through a worm gear translate their movements by means of electrical contacts. Thus the velocity and direction of the wind will be recorded. The instrument for the *Moreno* was ordered from France and registers sixteen directions. The direction and velocity of the wind are checked off by the pen on the registering chart in increments of one mile (1.609 km.), every time the wind changes. The maximum record for the chart is 62.13 miles (100 km.) and when the pen reaches this point it automatically returns to zero. The transmitter is located on the top of the forward cage mast and the registering apparatus in the central station. It requires five wires between transmitter and register and operates on approximately four primary cells.

Engine Revolution and Direction Indicator

Each of the three main turbine propelling shafts is equipped with a contact-maker for indicating the number of revolutions, a contact-maker for indicating the direction of the shaft, both

located in the engine room; a synchronizing clock and indicator also located in the engine room near the working platform; and three indicators located in the pilot house, forward conning tower, and central station. Eight wires are required to each indicator, three for the direction tell-tale and five for indicating the speed. Energy for operation is taken from the 15-volt busbars of the after interior communication switchboard. This apparatus is manufactured in Italy and is known as the Molinari speed indicator.

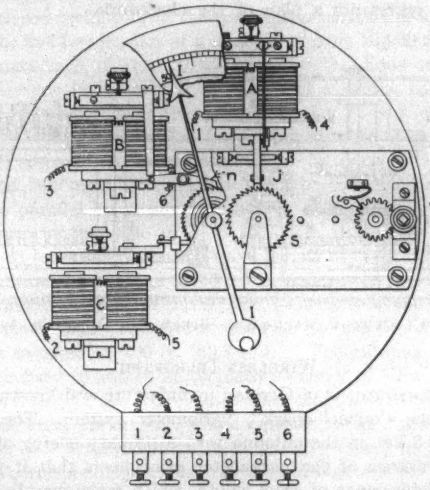


FIG. 29—INTERIOR VIEW OF SPEED AND DIRECTION INDICATOR

The direction contact-maker is a simple make-and-break contact operated directly from the shaft through chain and gearing.

The revolution contact-maker consists of a lignum-vitae cylinder carrying three brass sectors made flush with the periphery. It is located near the main shaft and arranged to turn at the same rate of speed. It is provided with two brushes insulated from each other and mounted on spring blocks.

The synchronizing clock controls the make-and-break contacts of the revolution contact-maker so that these impulses

may be interpreted by the indicator in measured time. A flat commutator provided with three segments insulated from each other is mounted in the clock and traversed by a metal brush. In this particular installation the "long-make" segment is designed to be maintained for a period of 15 seconds and the two "short-make" segments two seconds each. In this manner the speed during the fifteen seconds previous to reading the indicator is correctly measured.

The indicator consists of a train of clock gears actuated by a spring. Fig. 29 shows an internal view of the mechanism and Fig. 30 represents a plan of the clockwork.

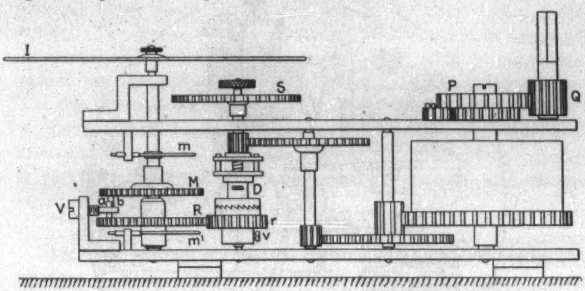


FIG. 30—CLOCKWORK MECHANISM—SPEED AND DIRECTION INDICATOR

WIRELESS TELEGRAPH

This apparatus is of German manufacture and known as the Telefunken "quench-spark", variometer system. The set is rated as 5 kw. in the antenna with a primary energy of 8 kw. The advantage of the variometer principle is that it permits of a variable range of wave length, which range may be chosen between 600 meters (1968 ft.) and 2000 meters (6560 ft.), depending upon the capacity of the aerial.

The motor-generator set is supplied with a double feeder from both of the main distribution switchboards. This set consists of a 220-volt d-c. motor of 18 h.p. and an a-c. generator rated approximately 8 kw., 500 cycles, 220 volts. The normal speed of the set is 1500 rev. per min. but can be varied for the purpose of altering the spark frequency and thereby the note of the transmitter about 20 per cent in either direction. The pitch of the transmitter note can also be adjusted very exactly by varying the field of the generator.

A straight core transformer steps up the 220-volt potential to 8000 volts. A primary choke coil is connected in series with the low-tension winding of the transformer. When the large capacity (5 Leyden jars) is used, the choke coil is used as a quenching coil in parallel with the emergency key, *i.e.*, this coil prevents severe sparking when the emergency key is brought into action. A secondary choke coil is connected in series with the high-tension winding of the transformer. This choke coil affords not only protection against high frequency, but also provides resonance between the transformer and the excitation current.

The closed oscillatory of the transmitter consists of a battery of four or five Leyden jars of a capacity of from 10,000 to 12,000 centimeters each (0.01 to 0.013 microfarad). Four or five of these jars can be connected by means of a sliding contact as may be required. Next there is provided a 16-part quenched spark gap which is air-cooled (maximum number of gaps to be used, 12) and a primary variometer. This latter consists of three fixed and two movable coils which can be connected either in series or parallel by means of a switch. This gives a variable inductance in the ratio of 1 to 16. The variometer scale is graduated so as to enable any wave length between 600 meters (1968 ft.) and 2000 meters (6560 ft.) to be adjusted in a moment.

The antenna will be of the L type, slanting from the foremast to the mainmast. The direct distance is 196 ft. (59.8 m.) and the hypotenuse 206 ft. (62.8 m.). The antenna capacity has been fixed to absorb an oscillatory energy of 5 kw. without loss, providing for the above stated wave lengths. In this circuit is the antenna variometer, which consists of six fixed and five movable coils arranged in two groups. By means of the scale and the corresponding curves, waves up to 1450 meters (4756 ft.) can be adjusted. For waves above this a lengthening coil is connected in series with the variometer which increases the wave range to 2000 meters (6560 ft.).

For receiving purposes a crystal detector is used It is claimed that this has the property of converting the high-frequency currents flowing through it into unidirectional currents. Therefore, it operates without any auxiliary e.m.f. and the receiving apparatus does not contain a local battery. It is also claimed that a very high degree of sensitiveness is shown when receiving at long distances. By its use the connections are also very much simplified. Underneath the variable receiving transformer

is a two-pole change-over switch marked "long waves" and 'short waves.' When the switch is on the position "short waves," the connections are as follows: Antenna, lengthening coil, variable condenser, earth or counterpoise. When the switch is on the position "long waves," the lengthening coil and variable condenser are connected in parallel to form a closed oscillatory circuit. The antenna now is connected to one pole of the condenser and the earth or counterpoise to the other.

With both methods of connection, the energy is transferred from the low-tension transformer coil which is in series with the antenna into the high-tension transformer coil. The latter forms, with the detector, an aperiodic circuit. This requires only one circuit to be tuned, viz.—for "short waves" the antenna circuit and for "long waves" the closed oscillatory circuit. Means are also provided for increasing the capacity of the receiver through an intermediate circuit whereby disturbances from other stations and atmospheric discharges may be avoided.

The design of this apparatus is such as to provide every means for the protection of the apparatus and operator from high tension. Behind the vertical frame of the receiver is a high-tension terminal and the high-tension switch, to which the leads from the antenna and the transmitter are connected. By this means the antenna is connected to the receiver and the transmitting circuit automatically interrupted.

This equipment has a guaranteed range of 1000 kilometers (621.3 miles) by day and 2100 kilometers (1304.7 miles) by night. That these guarantees will be exceeded in practise is seen in the report of trials on the sister ship *Rivadavia*, where communication was held between Boston and Colon, a distance of approximately 2000 miles (3218 kilometers).

Gyroscopic Compass

This apparatus is of German manufacture and is named, after its designer, the Anschütz gyro-compass. The design is based upon scientific principles laid down by the famous French philosopher Foucault. He arrived at the conclusion "that any gyro with only two degrees of freedom, *i.e.*, free to move in two planes only, will at any place on the earth's surface, other than the two poles, tend to set itself with its axis of rotation parallel to the axis of the earth itself, by reason of the relative rotations of the two bodies."

The practical value of this mechanism depends upon two

essential points: the oscillations must be effectively "damped" and the suspension must be as nearly frictionless as possible. If the gyro be considerably deflected from the meridian line it will swing for a very long time and in this condition many new forces are brought into play. In this compass the movement of air set up by the gyro-motor not only provides ventilation for the motor but also enables "damping" of the oscillations. A small rectangular outlet for the air is cut in the gyro case, the space in the base of the binnacle is designed so that the air blast will be free from air currents in the casing, and thus the forces tending to tilt the gyro from the horizontal are opposed.

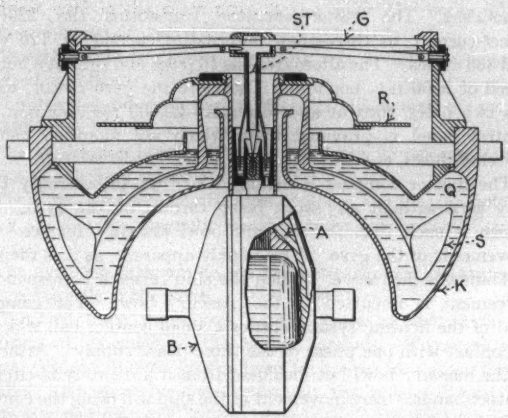


FIG. 33—SECTIONAL VIEW OF GYROSCOPIC COMPASS

As will be seen in Fig. 33, the complete gyro with motor casing, etc., is suspended by means of a circular, hollow, steel float in a bath of mercury. The mercury bowl is supported on gimbals in the same manner as any ordinary magnetic compass. The compass card is directly attached to the float and gyro and the gyro axle is directly under the north and south points of the card. The gyro always points due north and south. "In order to keep the whole floating system central a steel stem is fixed centrally in the top glass and the lower end of the stem dips into a small mercury cup carried on the top of the float. A similar connection is effected by a steel tube mounted concentrically

with the stem and a second mercury cup. These two sets of connections are electrically insulated from one another and from the general metal portions of the apparatus. These two connections carry two phases of a three-phase current to the motor of the gyro; the third phase reaches the motor through the mercury bowl, mercury and float. The motor of the gyro consists of a very small three-phase motor, the stator of which carries the windings, so that all the connections can be rigidly made. The rotor is rigidly fixed into the inside of the gyro flywheel itself." Special nickel steel is used throughout and the axle is supported on ball bearings of specially hard steel.

The master compass receives its energy from duplicate motor-generators. The motor-generator transforms the 220-volt direct-current to three-phase alternating-current at 120 volts and 333 cycles. The alternator has 16 poles and runs at a normal speed of 2500 rev. per min. Therefore the gyro motor, which has two poles, runs at approximately 20,000 rev. per min. A control panel is provided upon which are mounted meters, switches, fuses, etc.

The master compass is arranged so that the mercury bowl may turn without any work being thrown on the gyro. The design is such that the mercury bowl always "follows" the movements of the gyro. This is only apparent, as it is the ship and binnacle that move. When the ship turns, a corresponding movement is imparted to the mercury bowl. The compass card of the floating system carries a small contact ball which is in contact with one phase of the three-phase supply. Attached to the mercury bowl but insulated from it are two semi-circular contact bands. Any movement of the ship will bring the contact ball of the floating system into contact with these semi-circular bands. These contacts control a two-phase reversible motor mounted on the gimbal rings which when contact is made rotates the mercury bowl until the contact is broken and the circuit to reversible motor is open. This motor, as just described, receives its two-phase current from two of the three phases driving the gyro-motor.

The transmission of these motions to the receiving compasses is accomplished by means of a commutator mounted on the axle of the reversible motor. This commutator is constructed half of glass and half of silver. Four sets of brushes are arranged around the commutator at a distance of 120 deg. Connections are made from each of these points to each receiver. The motor

of the receiver has a stator similar to that of a star-connected three-phase motor. The star point of the stator is connected by a brush to the shuttle armature. This synchronizing arrangement is claimed to repeat these movements with an accuracy of one-sixth of one complete revolution. The receiver motor is operated by direct current through a special resistance which acts like a potentiometer resistance and which branches the direct current at 140 volts. The supply of direct current is controlled by the same switch which controls the alternating current so that any failure of the supply will not throw the receiver out of synchronism. The receiver motors are geared to their outer compass card in the same ratio as the reversible motor of the master compass is geared to the mercury bowl.

General points of interest regarding this device may be summarized as follows:

Peripheral speed of the gyro is 500 ft. (152.5 meters) per second or 340 miles (547.06 km.) per hour.

The air friction is so great that it absorbs 95 per cent of the power of the gyro-motor.

The directive force on the gyro-compass is approximately 15 times as great as a magnetic liquid compass, free from all disturbances.

The gyro-compass, unlike the magnetic compass, points to the true north pole of the earth.

Directive force diminishes as the poles of the earth are approached, because of the higher latitude. Therefore the actual distance moved by the gyro (in space) in a given time is smaller. No directive force exists at the poles. Every line there is a meridian.

The angular momentum about the axle of the gyro is always 100,000 times, and sometimes 1,000,000 times, as great as the component of the angular momentum due to precession.

The following numerical data obtained from an actual instrument may be of interest.

Righting coefficient at the equator	20,190 dyn. cm.
Moment of inertia	404×10^7 g. cm^2
Period of damped oscillation	4,110 seconds
Period of undamped oscillation	3,680 seconds

Conclusion

This equipment is the largest and most costly ever installed in this country, comprising 3000 electric lights, 4000 rated h.p.

and approximately 76 miles (122.3 km.) of cable. It is a noteworthy engineering achievement in that it was a departure from American practise in the use of 230 volts; in the employment of lead-covered, steel-armored, conductors; in the application of 220-volt tungsten lamps; in the use of electricity for the purpose of steering the vessel, operating the anchor, and the bilge pumps; and many more advances in the application of electrical power. The result has been fruitful to the American manufacturer in that he is now prepared to furnish standard 230-volt apparatus designed for use on shipboard. This equipment also stands as a practical solution of the many problems involved and as a working comparison with previous equipments.

DISCUSSION ON "ELECTRICAL EQUIPMENT OF THE ARGENTINE BATTLESHIP 'MORENO'" (HORNOR), PHILADELPHIA, PA., OCTOBER 12, 1914.

H. L. Hibbard: I should like to know if the author could tell us something about the results of the tests on the electrical equipments which he pointed out as particularly novel and new, for instance, steering gear, anchor windlass, bilge pumps and ammunition hoists. All those are more or less novel, and I thought perhaps he could give us some actual data from this ship or possibly from her sister ship.

Maxwell W. Day: I think there is a decided advantage in the 220-volt system, as far as the installation of the wire is concerned and also in the size of the controlling appliances, and also to some extent because of its effect on the design of the motors, especially in the larger sizes where commutator space can be saved, but, on the other hand, the motors require more turns, taking a greater amount of waste space for insulation and a greater use of commutating poles, so that for a larger number of the motors there is no saving in weight or expense.

The question of operating searchlights by balancer sets or by other means is something of a problem. It is not extremely easy to determine whether it is better to put in balancer sets and use the rheostats or to use that type of generator which will give practically a constant current. With the 125-volt system there is no particular advantage in this type of generator, because its efficiency is not as high as that of other types, so that there is considerable loss in the machine itself, and the difference in using a rheostat for 125 volts to steady the arc, which might take 65 volts, or the use of a motor-generator set, does not show any great advantage for the motor-generator when we take into account the weight to be carried on the ship, although there might be cases in which the heat developed on the rheostats would be sufficiently objectionable to cause a decision in favor of the other arrangement. But when you come to 220 volts, the case is somewhat different, and in some navies special motor-generators, that deliver practically a constant current and require no steadying resistance for the arc, have been quite extensively used.

The steel switchboard with the instruments insulated from it is German practise. It seems to have some advantages, but, of course, the question of insulation is more difficult than it is with a slate base or panel made entirely of insulating material. But some troubles that have been experienced with slate led the United States Navy to look for other substances, and on motor control panels the use of ebony asbestos wood in place of slate is becoming more extensive. The use of alternating current for the interior communication system is also a German practise, although the Germans use direct-current apparatus

also. I do not suppose the experience on the Argentine ships has been sufficiently extensive yet to decide on the relative merits so far as these ships are concerned.

The question that Mr. Hornor raised, of continuous waves as against a spark system of wireless telegraphy, is one of interest and the very successful results that have been obtained with the continuous wave system, both when developed by the arc and by high-frequency generators, have led to the desire to make use of some such system on smaller outfits, such as those used on vessels. But in the first place, there is a little difficulty in conveniently obtaining the short waves from the arc system, and to build a small high-frequency generator for short waves, is very expensive. Further, I understand that the short continuous waves are subject to a greater absorption in the atmosphere than those of the spark system, so that it seems rather doubtful to me that the continuous wave system will be extensively used for shipboard practise, at least in the near future.

I might say a word about the steering gear. As Mr. Hibbard knows, we have not advocated the contactor system for large equipments, but this particular case being one of 220 volts and of comparatively small power, it seemed to come within that range where contactors could be used with satisfaction. This particular system is not exactly what is being used in the United States Navy as regards the follow-up device. The United States Navy does not use follow-up devices, so that when the steering switch is turned to the right or left, the rudder moves to the right or left as long as the switch is left in that position or until the limit switch cuts it off, while on the earlier systems of electric steering gear, the amount of motion of the motor depended upon the amount of movement of the steering wheel or steering lever. It is rather difficult to make an electric follow-up device, and so in this case, and also in order to avoid adding to what is already an extensive electric equipment, the electric connecting leads between the steering gear itself and the steering stations were omitted and the control is operated by means of the same wire rope or hydraulic telemotor that operates the steam valve, the change-over connections being made in the steering room.

The *Moreno* has not had its trial trip, so that the tests at sea on this gear have not yet been made, and the final equipment on the *Rivadavia* has not had its full test, so that at present no information is available concerning the amount of power required or the general operation.

G. A. Pierce, Jr.: The wiring and the method of installation described were unique in this country and at the time this installation was designed. As Mr. Hornor stated, changes have been going on from time to time from a conduit system, which is not to be desired in any respect, and has been looked upon with suspicion since the early days when the change was made from a wooden molding to conduit. I think there will be no

occasion in the future to return to the conduit system, so that as regards the reduction in weight and space and also the increased facilities for inspection, the present form of construction in the *Moreno* is an advancement.

In the distribution of energy we find the same method that has always been employed in this country, that of separate dynamo rooms, with interconnecting bus feeders, necessarily large switchboards, a multiplicity of circuits of small cross-section paralleling each other for great lengths, with a corresponding number of protective devices, and numerous large and cumbersome hand starting devices for motors. The installation of 38 lighting circuits for a total of 3000 lights, or an average of 80 lights per circuit, and the use of 76 miles of wire in the installation of this size, is a continuance of past practise, the advantage of which has long since been questioned in this country.

While there are some innovations in the application of electricity on this vessel, the extreme application is not apparent. The communicating and lighting system compares with vessels of the same dimensions built in this country, and by a comparison of the power installation with other vessels we find but few exceptions, viz., windlass, fire pump, oil engine pumps, electro-mechanical hammer, ozonators, athletic horse, and moving picture machine. There is also in use a power system which appears to have been advisedly omitted in vessels built in this country, that is, the electric forced draft blowers. Since the successful construction of small steam turbines has been accomplished, the installation of electric motors for forced draft blowers results in a waste of space, weight and economy. While we desire to see the unlimited use of the electric motor, it is the speaker's opinion that this consideration will apply to all auxiliaries within the zone of the boiler and machinery spaces, where power is available direct from the boilers without transformation and control of the power is so extremely simplified.

In 1902, when the Russian battleship was constructed in Philadelphia, we had an electric steering gear, electric bilge pumps, ash hoists, and electricity in almost all of these features, with the exception of the windlass, fire pumps, oil engine pumps, electro-mechanical hammer, etc., which at that time had not been invented, or were not in use anywhere.

The use of 220 volts, double the voltage previously used, does not result in one-half the cost of wire as would be indicated, but only in the saving of three-tenths, with very little difference in the cost of wiring appliances and practically no difference in the cost of apparatus or labor for installation. The saving in weight follows very closely the same proportions as the cost of material, and when the additional cost and weight of balancer sets with wiring and additional protective devices and switchboard equipment for the control of searchlights is considered, the advantage of this increase in voltage is questionable, particularly in view of the advisability, since alkaline storage bat-

teries have become a commercial success, of installing storage batteries as auxiliaries for lighting and power for each battle unit.

The interior and exterior means of communication of information on this vessel are complete. The ever-increasing growth of this system in a battleship may, however, necessitate its remodeling in a very few months, as it is upon these systems the vessel must depend for its existence. If ready for action its presence must not be known until within range and if caught unawares or disabled it must attempt to escape and the vessel's own smoke or absence of it is employed for this purpose. We have recently learned of an invention to indicate automatically in any part of the vessel the color of the smoke emitted from the stack, and no doubt this system will be added in the near future to the ever-increasing means of communication on naval vessels.

Mr. Hornor has raised some question about the 220-volt lamps. Since the 220-volt tungsten lamps have been put on the market, we have been installing them in our shops, installing them on the bottom of cranes, and if there is anything that gets more vibration and shake than the bottom of a shop crane, it will hardly be found on a battleship.

As regards slate switchboards, I quite agree with the move our Government has made in the installation of composition in place of slate.

There appears to be no more necessity for duplicate dynamo rooms than for duplicate engine rooms. We believe that in the power plant of the future battleship there will be a number of units and a switchboard for supplying power for propelling the vessel and for all auxiliaries and lighting. The lighting and power for a deck or watertight section would be supplied from a common feeder with protective devices only at the apparatus, thus reducing weight, space and the cutting of bulkheads. All motors would be started either by contactors with a master controller or by automatic starter with a push button, depending upon the size and use of the motors. Lighting and power of each battle unit and indispensable auxiliary, such as steering gear, would be supplied by individual storage batteries of capacity for battle, thus reducing the size and increasing the efficiency of power installation.

We believe an installation of this character, in any or all of its features resembling the solution of the electric power engineering problem in large power stations on shore, and having the additional reserve for battle conditions at sea, to be not only a departure, but a decided advantage in economy, weight and space in comparison with any marine installations at the present date. Omitting the feature of electric propulsion, it is my opinion that the present practise can be improved upon by combining the dynamo rooms, combining and reducing the lighting and power circuits, using automatic starters and installing alkaline storage batteries, as previously stated.

Elmer A. Sperry: Mr. Hornor has given us a valuable paper. We find in the last paragraph on page 1588 "that any gyro with only two degrees of freedom, *i.e.*, free to move in two planes only," can be used as a compass. Now that is perfectly true; but that compass will only operate on land. When we take such a compass and put it on board ship, where it is subjected to all sorts of movements and motions, we encounter many real problems. These are due to the fact that the compass must of necessity be built pendulous, be supported in a Cardan or gimbal mounting, that it is subjected to acceleration and retardation pressures of the ship on which it is mounted during all sorts of maneuvers and changes of heading of the ship.

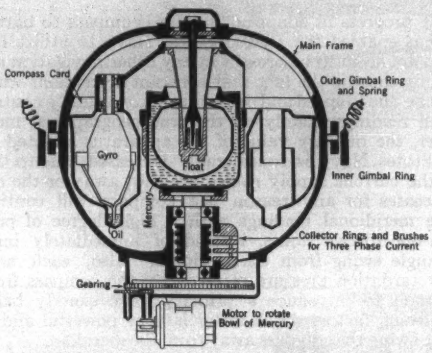


FIG. 1—SECTIONAL ELEVATION OF ANSCHÜTZ COMPASS HAVING THREE GYRO WHEELS

The compasses with which the Argentine battleships are equipped were purchased in 1910 or 1911 from a German manufacturer and contain one 6-in. gyro spinning at about 20,000 rev. per min. This was hung pendulous within an annular mercury bowl and was found to give serious deflections in azimuth, resulting from acceleration and retardation pressures and movements of the vessel referred to. No compasses with a single gyro wheel have been built by this concern for the past two or three years, but they have developed a new and very interesting compass containing three gyro wheels set at different angles to each other and coupled by certain links and bell-crank levers, pitman, etc., all the gyros being provided with centralizing springs, and they have adopted a follow-up system substantially similar to the one shown and described in a paper* on this sub-

*H. C. Ford, *The Electrically Driven Gyroscope in Marine Work*, this volume, p. 857, Part I.

ject read before the Institute last June—see Figs. 7 to 15.

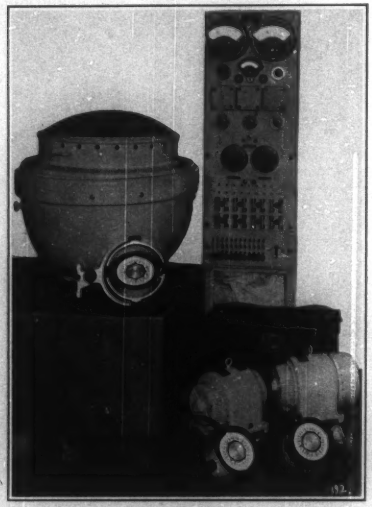
Inasmuch as no representation of this German product has been published in our annals, I am showing herewith, Fig. 1, a vertical section through the machine, giving a view of two of the three gyro wheels, three gyros being located equidistant around the circle. Each of these gyro wheels, it is stated, requires 1.1 amperes per phase at 120 volts, with a three-phase alternating current having a periodicity of 335 per second—in all, 3.3 amperes per phase. This is somewhat in excess of three times the current required by the American-made machine. The combined directive power, or useful function of this three-gyro compass is, however, only about 5/22 of that of the American-made machine.

Recent progress in adapting the gyro-compass to battle conditions has enabled the United States Navy to utilize features which do not seem to be present in any other navigation apparatus; among these is the fact that constant corrections which are found to be due to speed and course are automatically neutralized, giving all readings exactly on the true geographical meridian. Moreover, the military value of the apparatus adopted by the United States Navy is considerably increased, due to the fact that if the current supply cables are shot away or the current supply ceases for any reason the compass will continue to give true meridional readings with a high degree of precision for from one to two hours, instead of immediately initiating a wide-angle swing from the meridian. Also, each acceleration or retardation pressure received by the compass from the ship is made to introduce a primary force exactly balancing the disturbing factor, which latter is very powerful and would otherwise swing the compass away from the meridian.

The master compass is never used upon the bridge or in any of the major helmsman or steering positions, but is down in a position of safety below the water line and protected deck of the vessel. The azimuth, however, is required at distant points and is supplied by repeater compasses electrically connected to the master, reproducing the azimuth to the accuracy of a very slight fraction of a degree and with practically zero time lag. The American equipment has a unique feature consisting of means for synchronizing all or any of the distant repeaters and bringing them into exact harmony with the master, rather than trying to do it by telephone at each individual repeater.

Another unique feature is an independent device connected with the master compass, giving extremely accurate indications as to whether or not the master compass is on the exact meridian. Coupled with this is an alarm system which gives automatic and vigorous notification if for any reason the master compass is off the meridian even a fraction of a degree.

We have heard a great deal about the performance of submarines in the present war. This performance is all the more



[SPERRY]

FIG. 2—AMERICAN GYRO-COMPASS EQUIPMENT FOR SUBMARINE

[SPERRY]

FIG. 3—PORTABLE GYRO-COMPASS REPEATER

interesting owing to this being the first opportunity that this new form of craft has had to exhibit its powers in actual warfare. In this connection a photograph of the entire gyro-compass equipment of one such submarine might be of interest. Fig. 2 reproduces a photograph of the equipment of the English submarine *E*-9, which is reported to have performed some very startling feats near Cuxhaven at a considerable distance from its base, to which base the submarine again safely returned after, it is reported, having inflicted considerable damage on the enemy. The illustration shows the equipment which had been installed some six days prior to this performance. One of the repeater compasses of this equipment is provided with a long flexible cable and is portable (see Fig. 3), being capable of use in various parts of the ship, especially at the discharge valve of the torpedoes. The great precision with which the exact gyro azimuth of all periscopic observations may now be determined and also the high degree of precision with which the ship may thereafter be directed, gives assurance of accuracy of torpedo fire never heretofore attained, and probably unattainable by any other means.

I wish to express my great appreciation of Mr. Hornor's paper, which has gone into so many interesting details of these great ships which America is certainly proud of having built for our American neighbors.

H. L. Hibbard: After Mr. Sperry's gyroscopic oscillations, a discussion on some of the other points will perhaps seem rather commonplace, but I should like to make a few remarks on some of the things which Mr. Hornor outlined.

On the voltage question, there is, of course, a gain in the size of conductors and an appreciable gain in the size of controlling apparatus, especially on large auxiliaries, so that, aside from the slight objection, perhaps, to the use of as high voltage as this on the ship, the advantage seems to be on the side of the higher voltage.

As to the question of the banishment of the slate, it seems to me that has been a very good move, because all of us had considerable trouble with slate from breakage. When the company with which I am associated went to the Navy Department a few years ago and asked permission to supply asbestos switchboard panels, etc., on battleships, they gave consent very reluctantly, at our risk entirely. They now specify the asbestos material, which shows quite a change in opinion.

As regards electric steering gear, the chief advantages inherent in this type of apparatus were outlined pretty fully in my paper* presented at the May meeting in New York; it is not necessary to go into that further. I should like to ask Mr. Day if I correctly understood him to say that the decision as to the use of the contactor system on these ships was based on the ground of horse power only. Did that decide the matter?

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* *Electricity the Future Power for Steering Vessels*, this volume, p. 619, Part I.

Mr. Hornor brought up the question of whether or not it is of any real advantage to electrify the anchor windlass, and said that the principal advantage is in doing away with the steam pipes. That probably is the greatest advantage, doing away with the condensation of steam in those pipes and the weight of the piping, and also there is some saving in weight of the auxiliary itself. Further, an electric motor is a better machine than a steam engine, and you can put in more power in the same space than you can with a steam engine. The steam engine has to be designed for maximum torque, and sufficient strength to develop that torque, while in the motor you have an overload capacity available that does not compare with the condition in the steam engine. Mr. Hornor said that the anchor windlass on the *Moreno* had one-half the horse power of the steam engine equipment. That is probably a misunderstanding. I should like to ask him what is probably the horse power of the steam engine equipment.

One of the speakers made a reference to a dynamic brake in Fig. 16, which I should like to correct. The brake in the figure is a motor disk brake, on which point Mr. Day will bear me out. I assume there is a dynamic brake in the equipment also.

With Mr. Pierce, I think that Mr. Hornor's statement in his last paragraph ought not to go entirely unquestioned, to the effect that the installation of a number of the auxiliaries is a new departure from American practise, particularly in the United States Navy. As Mr. Pierce has said, on the Russian battleship constructed in Philadelphia before the *Moreno* was projected, most of these auxiliaries were installed. Also, the United States Navy at the time that this battleship was first started certainly had under test electric steering gears and had under consideration electric anchor windlasses, and long before the *Moreno* was constructed our navy had installations of both.

B. B. Bierer: There are a few things that I understood Mr. Pierce to say that have made me wish to make a few suggestions to those who are interested in the subject. One was the statement that there is no more use for two dynamo rooms on board a ship than there is for two engine rooms. That is correct, possibly, but I think there are, as a rule, two engine rooms on battleships, and sometimes three. We have tried the one dynamo room proposition and we have gone to two dynamo rooms or possibly an additional room for a Diesel engine above water for wireless, in case the dynamo rooms are submerged. We wish to take every precaution against placing the ship entirely out of commission. Of course the motive power might be placed out of commission with either one or two engine rooms, but that would still leave fighting power, provided we had a dynamo room in commission, as that is entirely electrically controlled—that is, lighting and fighting power and the wireless—and it would be a pretty dangerous proposition, even with the motive power out of commission, for someone else of at least smaller

fighting power to come too near. In addition to the use of the wireless and power—which is electrical power, the fighting power of the ship—of course you can see very readily the advantages of having a number of means by which a ship cannot be put entirely out of commission.

I was very much interested in the remarks Mr. Pierce made in reference to the question of conduit or armored cable, because I have been associated with the use of conduit for a great many years, and the advantages that were claimed in the adoption of conduit have not been secured in the Navy, although we stuck to it for many years. One is water-tightness. That was impossible. The conduit installation was supposed to be water-tight, both in itself and where it passed through water-tight bulkheads, but in collisions that have occurred, when the compartment in collision was shut off and pumped out to put a patch on, water simply poured into the compartment and it was found it came through the conduit—simply had leaked in in streams. Now in addition to this leaking in in streams, when the decks are washed down and various things of that kind done, moisture gets into the conduit. It accumulates a mass of muck and corruption there at the end of a few years, everywhere the moisture gets in, and it is almost impossible to keep it out anywhere, any time or any place. That breaks down the insulation and one pretty soon finds so many grounds in the electrical installation of the ship, that were the ship to be used as a fighting machine and require all her electrical power, she would be absolutely unable to come up to the requirements.

Armored cable absolutely does away with grounds in the cable itself. Of course, there may be grounds in the junction boxes, connection boxes, and fixtures, but as far as the cable is concerned, unless that is pierced there are no grounds possible. The lead around the fiber insulation of the wire itself makes a perfectly water-tight seal. Then the mechanical protection—the wire braid—is very strong. You can bend that. You can put the end of the cable in a vise and bend it back and forth "until the cows come home," as they say, and it is still as good as ever, and the lead itself will break before the wire braid will.

Now as to the question of induction. We formerly used a great deal of what we call open work wiring instead of the conduit, to lessen weight and lessen this mass of pipes running around and underneath the beams—dust collectors and vermin collectors and having a most unsightly appearance. The question of induction, and wireless and other electric currents from one cable to another, was such that a short time—I don't mean to say a short space of time necessarily, but a short time in the life of a battleship—two or three years—would put the electrical installation out of commission as far as grounds are concerned. It had to be all gone over again every year. Where there is any trouble in conduit installation, it means tearing out the whole thing and putting in new. These are points in the consideration

of conduit and wiring that come up from experience and are absolutely necessary to consider.

We do not have that small kuhlo (concentric) wire in use in our service, but it looks very good to me. It is neat, though a little expensive, and it certainly would be extremely desirable from a naval viewpoint.

J. H. Linnard: The great difficulty with the application of electricity to the windlass engine is the fact that the normal condition of a windlass when it is being operated is to be stalled, and you never know when that is going to happen. It stops at the most unexpected times. Now the question is, if you get the armature of your motor working at a speed that gives very considerable inertia forces, how are you going to deal with that when the unexpected jam occurs, as it practically always does occur, when the anchors are being weighed? I haven't heard how that matter has been dealt with in these recent electrical installations for windlass engines, so that I do not feel able to speak about the matter.

I am glad to hear Commander Bierer tell us that conduit has been abolished in the later ships of the Navy, because from the point of view of a naval constructor it was precisely those difficulties of the weight and lack of water-tightness of conduit that always caused us to be on our knees to the Electrical Department to abolish it, but at that time they saw so many advantages in the use of conduit that they were unwilling to do so.

W. F. Cochrane: I appreciate the opportunity to join in the discussion of this paper, remarkable for its completeness, before this society that has done more to enlarge the field of electricity than any other organization in this or any other country. In fact, I think I may say that a great deal of the electrical supremacy of the American manufacturer is due to this Institute through its meetings and its frank and open criticisms.

Any criticism I may make of the paper that has just been read will be from the battle point of view and from that of experience in the practical handling of electrical installations on board ship, and not from the standpoint of an expert electrician, as my electrical knowledge is limited to the practical handling of electrical installations on board ship.

The keynote of any installation for a battleship should be simplicity. If possible, only one voltage should be used on the entire ship for all purposes. The number of feeders should be reduced to a minimum and all efforts should be turned towards the one great objective of making the installation as simple as possible. The character of electricians available makes this element of simplicity imperative. The United States Navy has been rightly named "a great educational institution." The electricians that we have in the navy are men who enlist and have a small amount of experience and knowledge in electricity. These men are then sent to an electrical school where they receive instruction in the various appliances used on board

ship. The period of time occupied by this is about one year; the man is then sent to some ship in an inferior position as an electrician. From this you can easily see how important the item of simplicity becomes in the design of the electrical installation of a battleship.

In the installation just described, I do not consider that simplicity has been attained to the extent that it could have been. First, in the use of 230 volts, for which a saving is claimed, but which we may seriously doubt, due to the installation of transformers to enable the searchlight system to be operated at the most advantageous voltage. I am not in favor of the use of high voltages on board ship unless a great saving in either weight or cost, or a simplification of the systems, will result therefrom. One disadvantage is that the use of higher voltage leads to considerably great liability to insulation troubles.

The installation of great numbers of protective devices, in my opinion, serves no useful purpose. There should not be any necessity for a protective device such as a circuit breaker, except at the switchboard. The line itself should require no protection. A fuse at the particular piece of apparatus on the line, whether it be a motor, indicator or any electrical instrument, should be ample protection for this installation.

In the matter of lighting circuits, we have, in the installation described, two battle lighting circuits, one white and one blue. I personally am not in favor of more than one battle lighting circuit, although the blue light circuit has its advantage in the fact that blue lights can be used in the gun deck compartments and will show very little light outside, but there should not be any necessity for general lighting around the compartment of a broadside gun. In turrets and in enclosed places, white lights are used as they cannot be seen from the outside. The greatest protection a battleship can have against submarines and destroyers operating at night is absolute darkness. The blue light circuit may not give much light, but it will certainly be easier to discover a battleship with a blue light circuit lighted than one with absolutely no light showing.

In regard to the battle lighting and power circuits of a battleship, I am heartily in favor of the use of alkaline storage batteries for the battle service. I believe that this is the best solution of the many problems confronting the designer of an electrical installation on board a battleship, because the storage battery can be installed in the turret to operate everything in the turret, and then the only possible way to affect the power units of the turret would be to put the turret itself out of commission.

In regard to interior communications, battle lighting, it is much better if operated by a storage battery which can be placed in such a position that before it is injured or any of the leads are injured, the ship itself will be practically destroyed insofar as she is valuable as a fighting unit. We may also say that an installation of this kind will save considerable space and some

weight, as it will do away with the requirement of two dynamo rooms and it will be possible to place the dynamo room as an auxiliary to the engine room, or combine the two into one power plant, in case electric propulsion is adopted for battleships, as most of us believe it will be in the near future. It will combine the dynamo room and engine room in one locality that can be protected to such an extent that it will be practically impossible to injure the installation in any way.

The design of interior and exterior means of communication on a battleship is subject to practically constant change, and it is believed that these systems will be radically changed in the near future, with the advent of an invention to indicate automatically, in any part of the vessel, the color of smoke emitted from the stack, and with the application of the principles involved in this invention to general methods of interior communication in time of battle.

To sum up, the electrical equipment of the Argentine battleship *Moreno* is the most complete that I have ever seen, although I doubt the battle usefulness of a great many features that have been installed on board. I think it would be far more creditable if the designer had been able to say, " we have an installation that will produce the same results as the installation that was placed in the last battleship built, and we have only used half the miles of wire and half the fixtures and we only have half the number of protective devices and half the number of automatic starters and auxiliary instruments."

Clyde S. McDowell: Mr. Hornor described a method of telling the trueness of the searchlight mirror which is known as the " screen test;" it is done by photographing a reflected image of parallel wires or lines. However, this only shows the trueness of the grinding, and is not an indication of whether or not the mirror is parabolic. In addition to testing for trueness of grinding the mirrors should be tested for over-all efficiency. This can be done by taking a mirror and placing at the focus a concentrated-filament tungsten lamp or other source of light, and, at a distance far enough away so that the light varies inversely as the square of the distance, measuring by photometer across the beam in both directions the actual light received on the distant screen. In this method the source of light is known and always the same, and a true indication of the value of the mirror is obtained. It has been found by tests that one mirror which showed by the screen test to be perfectly true in its grinding, put up against another mirror which showed marked irregularities in grinding, did not show as good results in actual illumination, due undoubtedly to the structure of the glass, the thickness of the glass, or the color of the glass.

There was a question brought up as to the 220- and 110-volt systems on board ship for lighting. We have made numerous tests on vibrating platforms and lamps in both horizontal and vertical position, both 220- and 110-volt lamps—these platforms

vibrating at the regular period of vibration of a ship—and in the sizes of higher wattage we find that the 220-volt lamps have as long life as the 110-volt lamps. That test is made with the lights on half the time and off half the time, so that the regular service conditions are obtained.

On the question of using a balancer set for searchlights on 220 volts, that is probably a good engineering way to cover it, but on some of our larger ships we are using 220 volts and have a balancer set to take the unbalanced lighting load large enough to take in addition the unbalanced load of four searchlights, which would be putting the searchlights on the lighting circuit.

On the question of doing away with conduit, one of the reasons why conduit has proved unsuccessful on board ship, especially in the fire rooms and engine rooms, has been the condensation in the conduit, irrespective of whether it was water-tight or not. The great changes in temperature that take place, cause the conduit to fill up with water.

Maxwell W. Day: A remark was made about the desirability of having the dynamo plant independent of the propelling machinery. This has just been illustrated in a recent naval battle, where the steam pipe of one of the German destroyers was shot in two, and the boat was seen to be enveloped in a cloud of steam, but frequent puffs of the gun were seen through it. Of course this was not an electrically operated gun, being only 3½ inches, but it showed that the battery could be continued in action after the propelling machinery is out of order. It seems to me that one of the best ways to promote the independence of the dynamo plant is to bring into more extensive use oil-engine-driven sets.

Naval Constructor Linnard spoke of the way of taking care of the anchor windlass in weighing the anchor, where the engine simply would slow down and stop. An ordinary control equipment of electric motors would naturally blow the circuit breaker. As mentioned in Mr. Hornor's paper, a step-back relay is provided, which will open some of the secondary connections of the accelerating contactors, and reinsert a certain amount of resistance in the armature circuit. This will allow the armature to receive about 1¼ times full-load current, or, of course, it can be adjusted for any other desired value. This was tested on the *Rivadavia* by setting the brake on the wildcat and screwing it down until it became sufficient to trip this step-back relay, when the motor stopped, and the current amounted to about 25 per cent overload.

Mr. Hibbard asked if we determined our recommendation for contactors solely on the horse power. It is primarily on current capacity, which would be also according to horse power, assuming voltage unchanged, and we have felt that in very large sizes frequent operation of the contactors successfully is quite a serious problem, and therefore we recommend the variable-voltage system for large units; but with only 150 h.p.,

and where 220 volts is used, as here, it brings it within the class of moderate-sized equipments.

Mention has been made of the disk brake on the steering gear motor, shown in Fig. 16. This brake is quite small, because we depend principally on the dynamic brake itself to stop the armature, or begin the stopping of it. The disk brake, which is a little slower in action, finishes the work, and holds the armature in a state of rest.

In regard to the material for switchboard and control panels, what is used for this purpose is ebony asbestos wood, called by some, asbestos lumber impregnated. It takes a fine polish, has very much the appearance of slate, and is preferable, I think, to what ordinarily goes by the name of asbestos lumber.

L. C. Porter: The chief difficulty in making 220-volt tungsten lamps is with the arcing. Where the leading-in wires come out of the stem, the current is apt to jump across. Considerable improvement has been made in this respect since the first lamps were put out, but at present the 220-volt lamps are not so free from arcs as the 110-volt, though the percentage of arcs is relatively small. Another difficulty encountered with the 220-volt lamp is what we call "locking" of the filaments. This consists of the filaments jarring together and short-circuiting a section, thus considerably shortening the life of the lamp.

The efficiency of the 220-volt lamp is also somewhat lower than that of the corresponding 110-volt lamp. For example, the 25-watt 110-volt lamp operates at 1.05 watts per candle; while the 25-watt 220-volt lamp operates at 1.2 watts per candle.

There are two types of filament construction used in the 220-volt lamps. In the regular pear-shaped bulb, with which you are all familiar, we use simply a straight wire filament. That filament is shaped on a form before it is placed in the lamp. It is also mounted on flexible anchors, which make the lamp mechanically just as strong as the 110-volt lamp. In the round bulb, and in the tubular bulb, in order to get the filament in the small bulb, we have to wind the filament into a helix and then mount it, which again lowers the efficiency of the lamp by cooling the filament at the anchors. In these lamps 1.06 watts per candle is the lowest specific consumption that we are able to obtain. Life tests on the 220-volt lamps of 25-, 40- or 60-watt sizes, under laboratory conditions, have shown that we obtain 2000 hours' life out of the straight filament and from 1200 to 1800 out of the coiled filament.

The tests which we have made on the lamps at the laboratory consist of vibration tests and bumper tests. The bumper test is made in this manner: We have an inclined board, at the end of which a lamp is hung on a piece of lamp cord. The board is graduated in inches and a round ball, weighing 110 grams, is rolled down this board, which has an elevation of 11½ deg. The ball is allowed to bump against the lamps, both cold and burning. Of course, lamps when burning are not quite so brittle

as when cold, because the filament is softer when it is hot. Often with the lamps burning we can roll this ball from 40 to 60 in. against the lamp before the filament breaks, and that is just as far as we are able to roll it with the 110-volt lamps. In other words, the filament is mechanically as strong as the 110-volt lamp filament.

The vibration test is made upon a wheel with arms on it (similar to the spokes of a wheel), and the lamps are mounted at the ends of the arms. There is a series of cogs over which these arms pass. This wheel is revolved over the cogs at various speeds, with a little spring under each arm to pull it down, giving it a very severe vibration; in fact, we can get almost any vibration that we want. On that wheel I have seen as severe a vibration as is obtained on battleships under operating conditions. I have been aboard some of the ships during target practise, full-power run and a few other severe trials, and feel that in this test we give the lamps just as severe treatment as they obtain on the ships in actual service. However, as I stated before, the trouble is not mechanical breakage, but locking of the filaments, which shortens the life.

It seems to me, therefore, that if there is a decided call for the 220-volt lamps, there need be no hesitation in installing them on the ships. Of course, it is a harder lamp to make, is more expensive, and is not made in such large quantities as the 110-volt lamps. For these reasons, from the lamp manufacturer's standpoint, we should prefer to furnish the 110-volt lamp, because it is a lamp with which we have had a great deal of experience. We have not had the 220-volt lamps under service conditions in any great numbers, and before being absolutely sure that they will be satisfactory, the most I can say is that we would suggest that, if possible, the same arrangement be made as was made with the 110-volt lamps; namely, that about 2000 lamps be put on a ship and tested in service. This, it seems to me, is the only sure trial which will absolutely prove the merit of the 220-volt lamp.

H. A. Hornor: I should like to explain an evident misinterpretation of the last paragraph of my paper. The various applications therein referred to constituted departures from American practise at the time the contract for the *Moreno* was signed, Many of these applications were in an experimental stage at that time, and during the five years of construction of the *Moreno* naturally these applications have become requirements. As an illustration of this, the United States battleships *Arkansas* and *Wyoming* were not equipped with electric bilge pumps, electric steering gear, and electric anchor windlass; whereas the United States battleships *Texas* and *New York* were equipped with electric steering and electric bilge pumps but not electric anchor windlass. The later United States battleships are to be equipped with all these outfits. I did not intend my remarks to convey the impression that I was comparing previous foreign war vessels built in this country.

The horse power of the electric anchor windlass on the *Moreno* is a little less than ⅓ the horse power required of the steam equipment. It is to be noted that one anchor was raised in about 60 fathoms of water by this equipment using about 35 horse power after the anchor had "broken away."

I believe that there are many advantages in the use of 230 volts for such installations. I have heard it stated that some nations were considering the advisability of increasing the voltage to 500. If proper insulation is provided and all questions of detail carefully looked after, I see no reason why 230 volts should give any more trouble than the present 125-volt system. In this connection I was glad to hear the remarks on the comparative merits of the 220-volt tungsten lamp. On the ground of simplicity of installation, the use of this voltage would be preferable to the complications that would ensue from a system of double voltages. In view of the fact that the power load is now by far the greatest in point of importance it would seem preferable to design the installation so as to satisfy this demand first. The searchlights could very well be taken care of by rotary balancer sets in order to do away with the difficulties involved in large permanent rheostats. Such apparatus when tested on the *Moreno* gave unqualified satisfaction.

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ELECTRICAL FEATURES OF THE U. S. RECLAMATION SERVICE

BY F. H. NEWELL

ABSTRACT OF PAPER

The operations of the U. S. Reclamation Service are of interest to electrical engineers not only in some of the novel developments and applications of power but also as illustrating the efforts of the federal government in the construction of works of general public utility.

One of the most interesting features is the question of cost of government work, much of which in this case is executed under pioneer conditions. These costs are carefully recorded and include all of the overhead or general expenses. These costs show that during 1913, for the various plants there was a range from 0.68 cent per kelvin or kw-hr. up to 2.873 cents. The power not needed for construction purposes or for operating irrigation works is being sold at rates of 1.5 cents per kw-hr., and for excess power as low as 0.5 cent, up to 2 cents or over. For heating the rate charged per month from June 1 to September 1 per device per 1000 watts is $1.50.

The experience obtained is illustrating the fact that it is practicable for the government to build and operate plants of this kind and sell the power at cost, in connection with other enterprises and with general satisfaction to the consumer.

The power plants will be paid for without profit or interest and the operations transferred as soon as practicable to the communities benefited by them.

THE electrical engineer as a professional man finds much of interest in the works executed by the United States Reclamation Service and in the plans under consideration for further enterprises. Electrical development and transmission enter largely, not only into the construction, but also into the operation of the works for the irrigation of arid lands, which are being built under the terms of the act of June 17, 1902. This act sets aside the proceeds from the disposal of public lands in the western arid and semi-arid states, for the purpose of survey, construction, operation, and maintenance of works for the storage and distribution of water for irrigation and reclamation of arid lands.

Aside from his purely professional interest, the electrical engineer, as a citizen, is concerned in all of these matters which have to do with the upbuilding of the United States, the utiliza-

tion of its natural resources, and the increase of the prosperity and happiness of the commonwealth. Both of these phases, that of interest to the professional man and to the citizen, are briefly discussed in the following paragraphs, the attempt being made to describe in a concise way the works which have been or are being built and to give the relationship of these to the larger economic or political problems of the country.

Object. The main purpose in the development of electric energy by the Reclamation Service is the production of cheap power for raising underground water to the surface or surface waters to lands which are too high to be reached by the ordinary gravity method throughout. There are other uses, however, to which this energy can be economically applied. Taking these in the sequence of events they may be summed up as follows:

1. *Transportation.* This includes the building and operation of works for transporting material to be used in construction.

2. *Construction.* This embraces all electrical devices employed in the handling of materials, in lighting the works and in facilitating other operations.

3. *Pumping.* As previously stated, this is the most important use of the electric energy which is developed in the course of the work of the Reclamation Service.

4. *Commercial.* An important outgrowth of the above is the disposal of excess electric energy developed largely in connection with pumping, but sold for lighting or industrial purposes, proceeds being used to assist in defraying the cost of the pumping of water for agricultural purposes.

Methods. The methods of development of electrical energy and the character of machinery employed are largely those of the usual commercial practise, the attempt being made to keep well in the lead. In some cases, notable advances have been made over customary methods. As might be inferred, the largest amount of energy is developed by the use of water power. In other words, hydroelectric planning and construction form the principal feature of this class of engineering works. There are, however, a number of relatively small plants in which the energy is derived from the consumption of fuel either utilized in the production of steam or in the more direct use of oil or gas in the ordinary engines developed for this purpose.

Costs. In all of this work undertaken by the Reclamation Service, not only in connection with electrical development and

use, but also in its other operations, careful records are maintained of the actual cost of the various items. Quite frequently in statements of cost prepared by other bureaus of the government, the matter of overhead charges has been neglected or many items which are properly to be considered in this connection are not entered because they are carried on regular appropriations. These neglected items usually consist of salaries of permanent officials whose time is largely devoted to the particular work in hand but is not charged to it. For this reason, the costs prepared by the Reclamation Service give, perhaps, a more accurate conception of actual and necessary expenditures than those usually obtainable from records kept by government bureaus.

Without entering into an elaborate discussion of these costs, it may be said that they range, in general, from a few mills, or even less, per kilowatt-hour for power developed in large quantities by hydroelectric plants, up to a few cents per kilowatt-hour as developed by steam plants.

The costs for 1913 are shown in the following table:

POWER PLANTS OPERATED BY RECLAMATION SERVICE IN 1913.

Reclamation project	Power plant	Location	Type	Capacity kw.	Annual load factor, per cent	Output in kw-hr.	Cost in cents per kw-hr.-(a)
Salt River.....	Three plants	Arizona	Hydro-electric	8,560	12.7	9,518,570	0.810
Boise.....	Boise	Boise R. Idaho	"	1,875	43.2	7,082,123	0.268
Minidoka	Minidoka	Snake R. Idaho	"	7,000	46.1	28,265,287	0.126
Truckee-Carson	Lahontan	Lahontan Nevada	"	1,250	8.5	930,360	1.118
Rio Grande....	Elephant Butte	Elephant Butte Dam New Mex.	Steam turbine elec.	1,875	12.6	2,065,840	2.873
No. Dakota Pumping.....	Williston	Near Williston N.D.	"	1,150	11.4	1,145,337	2.614
Strawberry Valley.....	Spanish Fork	Near Sp. Fork, Utah	Hydro-elec.	850	11.6	861,705	2.572(b)

(a) These costs are at power plant switchboards and include in addition to all maintenance and operating expenses, general expense and plant depreciation.

(b) Includes heavy canal expense.

For purposes of comparison with the above statements of cost, it may be said that it is a popular belief that the cost of manufacturing electric power at Niagara Falls is about 0.2 cent

per kilowatt-hour, and that for power development in blocks of say 5000 kilowatts and upward, it is more economical to erect a modern steam power plant at Buffalo than it is to transmit this energy from Niagara Falls at a cost at Buffalo of say 2½ mills per kilowatt-hour. In other words, the modern economy of the steam engine and generator is such that when fuel is cheap, current can be manufactured on the ground and utilized without transformation more economically than it can be transformed and transmitted over a considerable distance. The cheapest hydroelectric power reported is in the South, stated at 0.1 cent per kilowatt-hour, or about $6 per h.p. per year.

On the Minidoka Project of the Reclamation Service, the cost of producing power at the plant switchboard is seen from the above table to be about 1¼ mills. The surplus power over that needed for irrigation pumping on this project is sold as a by-product. For this purpose the Reclamation Service contracts with a local company or distributor, protecting the ultimate consumer by provisions in the contract limiting the maximum rates chargeable by the distributor. These rates are shown in the table on the following page.

Fallacies. In developing hydroelectric power for irrigation pumping, it has been necessary to meet many popular fallacies concerning the cheapness of water power. It is generally assumed that because the water is flowing more or less continuously throughout the year, making possible a large amount of power, that therefore, the power itself must necessarily be cheap. Little consideration is given to the large first cost of installation, of development of the power, to the interest on the investment and particularly to the depreciation.

Few people outside of the profession of electrical engineering understand that the utilization of the natural water power is accompanied by heavy expense, notably in fixed charges for interest and depreciation, and that these may far exceed the more obvious costs of a steam plant. Obsolescence also must be considered, especially in waterwheel development. Great improvements have been made along that line, so important that no up-to-date power plant manager can ignore taking advantage of them. While in purely electrical apparatus obsolescence is becoming less and less of a large factor, if the plant is properly designed, yet it must be considered. The heavy item and one not usually appreciated is, as above stated, the interest, depreciation and other fixed charges inseparable from a large

capital investment. It is not an uncommon thing for a unit of hydroelectric power generation transmission and transformation at the substation to run into $250 to $300 per kw., while a steam plant in large sizes may not exceed $45 to $60, or at the most $75 per kw. On the other hand, the depreciation of a

IDAHO—MINIDOKA PROJECT.
Electric Power for Commercial Use.
(Contracts Nos. 322, 323 & 326 and supplemental contracts.)

Monthly Rates.			
To distributor		To consumer	
Per incandescent light of 15 watts	$0.03	For 20 incandescent, 15 watts 5c, each additional light	$1.50
Per incandescent light of 15-60 watts	0.10	For 5 incandescent, 15-60 watts 25 c. each additional light	1.50
Per incandescent light over 60 watts for each 60 watts or frac.	0.10	Per light over 60 watts, for each 60 watts or frac	0.25
Per arc light, 700 watts to 10 p. m.	1.50	Per arc, 700 watts to 10 p. m.	2.50
Per arc light, 700 watts all night	2.50	" " " " all night	4.00
Heating Rates.			
Per device, Sept. 1—June 1	$0.50	Per device 1000 watts Sept. 1-June1	$1.00
Per device per 1000 watts June 1—Sept. 1	1.50	Per device per 1000 watts June 1—Sept. 1	2.50
Flat-Iron Rates			
Per flat-iron 700 watts	$0.25	Per flat-iron 700 watts	$0.50
Metered light and appliance rates, per kw-hr.			
First 2500 kw-hr. in mo	$0.027	First 25 kw-hr. in mo	0.07
For 2,500-5,000 kw-hr. in mo	0.025	For 25-50 kw-hr. in mo	0.06½
For 5,000-10,000 " " "	0.023	For 50-100 " " "	0.06
In excess of 10,000 " " "	0.021	In excess of 100 " "	0.05½
Power Rates, per kw-hr.			
First 2,000 kw-hr. in mo	$0.01	First 100 kw-hr. in mo	$0.05
For 2,000- 3,000 (do)	0.007	For 100-200 (do)	0.04
For 3,000- 5,000 "	0.0055	" 200-500 "	0.03
		" 500-1000 "	0.015
For 5,000-10,000 "	0.0053	" 1000-2000 "	0.008
		" 2000-5000 "	0.007
For 10,000-25,000 "	0.0051	" 5000-50000 "	0.0063
		" 50000-75000 "	0.0060
In excess of 25,000 "	0.0050	" 75000-100000 "	0.0057
		In excess of 100000 "	0.0055

steam plant and repairs of the same are much in excess of the hydroelectric system as a whole, but this does not modify the fact that it is often cheaper to build steam plants to meet load conditions rather than to furnish it by hydroelectric power. This, as above stated, it is difficult to bring to public comprehen-

sion, namely, that electric power developed from water power is sometimes more expensive than the equivalent amount of power developed, when needed, by economically operated steam or gas engines.

One of the popular misapprehensions which has given rise to considerable disappointment to the settlers on government projects is the lack of appreciation of the fact that electric energy after being developed must be raised to high voltage for long distance transmission and again transformed before distributing to the consumer and that such transforming apparatus is quite expensive.

The farmer, seeing a high-tension line skirting his farm, cannot readily be made to understand why he cannot purchase a small amount of electricity for use on his farm or in his house. It is necessary to explain to him that the difference is almost as great as would be in a case where he might argue that because a tree grows on his land, he should be able to get his tables and chairs at relatively small cost! The transformation of a tree into a chair may be as difficult as the transformation of the high-tension electricity into a form such that he can safely use it around his house or barn.

There has also been an exaggeration in the minds of the people in the communities on some of the government projects of the importance to them of the power plants which have been built in connection with the pumping and related work. They seem to think that these are an asset which they can utilize for more or less speculative purposes and that the earnings of these power plants will notably reduce the cost of the irrigation works and possibly save the water users from any expenditure. They have an exaggerated idea of the earning power of these works, not appreciating that many of them can be operated only during the irrigation season, and that electric power developed under these circumstances has small commercial value. They have heard of the great earnings of the water power monopolies and picture to themselves the advantages of securing a monopoly of this kind which they can handle to their own immediate profit, forgetting that the manufacture and sale of electricity developed by water power is a highly specialized business, like the manufacture of any other commodity, and one which is not always financially successful, and then only because handled by men of exceptional ability.

Uses. As above stated, many of the uses for electric power developed by the Reclamation Service are those in connection

with transportation of materials and construction of works. There is not much of novelty to be considered in this connection, as the devices employed are usually standard in design. They consist of light electric railroads, such as are needed in construction of tunnels and in similar work, and apparatus for the operation of cement plants, cableways, hoists, excavating machinery, etc., lighting plants being, of course, an important adjunct.

Pumping, however, forms the great and principal use of the electric power development and there were installed 9235 h.p. in permanent pumping plants used in 1913, in addition to numerous small drainage installations, semi-portable and intermittently used. The cost, including all overhead charges and depreciation, has been estimated to average about one cent per acre-foot raised one foot, ranging from 0.3 cent per acre-foot at Minidoka, upward. That is to say, an amount of water covering an acre one foot in depth, or 43,560 cubic feet, can be raised to a height of 50 feet for fifty cents.

In comparison with this, water raised by the ordinary small steam or gasoline pumping plant built by associations of farmers throughout the arid regions is probably costing from 7 to 10 cents per acre-foot raised one foot, including, as above stated, interest and depreciation. With better and more economical devices for raising larger quantities the cost may be cut down to five cents, or even, under exceptional conditions, as low as three cents, while those of the government works, as above stated, may run as low as at Minikoda in 1913 when it averaged 0.346 cent.

Sales. Sales of power for commercial and other purposes are made at varying rates, dependent mainly upon the cost of development. As a rule, the electric energy is sold by the government as nearly as possible at cost. The reason that the cost varies so widely is due primarily to the difference in conditions of development, and, secondarily, to the conditions attached to the sale, particularly as to the continuity of demand by the consumer.

The ordinary price or what may be considered as a standard of the Reclamation Service for current for commercial purposes in large lots is about 1.5 cents per kw-hr. Under extraordinary conditions where excess power is sold whenever developed and is used as an auxiliary for steam power, the price has been as low as 0.75 cent per kw-hr. or even 0.5 cent.

In one case in Utah the Reclamation Service is selling at 0.8 cent per kw-hr., with a guaranteed minimum charge of $225 per calendar month. While this is a comparatively low rate, it is not as low as the minimum rate given the Reclamation Service in purchasing power in Montana, where a company has built a considerable amount of transmission lines in order to secure the business of the Reclamation Service in the construction of the Sun River project.

The essential feature in these extraordinary low prices is that the Reclamation Service is selling surplus power and that there are two unusual clauses relieving the United States from obligation to furnish power in case it should become inconvenient to do so, as follows:

"The United States shall have the right and privilege to shut down its power plant and cease serving electric energy at any time in order to make necessary repairs or additions to transmission lines, canals, or machinery."

Also it is stated that "in case of the shortage of power due to lack of water, or if the demand for power for construction purposes causes the furnishing of power to the city to impede the progress of construction work on the project, the United States reserves the right and privilege to cut off the power until such time as it is possible to furnish power without impeding the progress of construction work."

The rates charged for heating and similar purposes vary widely, as above noted, dependent upon there being an excess of energy during the winter season when water is not pumped for irrigation. Not being sold or disposed of for profit, the rates for sale approximate usually, as above stated, nearly the actual cost, these being so low in some cases as to compete with coal at $7 per ton in heating houses and in cooking.

Power Development. The following figures give in concise form and in alphabetic order by states the power already developed, together with the total proposed or possible power and the output. Following the tables there is also given a brief description of some of the more important power plants with their chief characteristics. The most notable of these is on the Salt River project in Arizona, the principal power plant being located at Roosevelt dam and the subsidiary power plants along the canals which are supplied with water largely from the reservoir created by this dam.

POWER DEVELOPMENT* (Water Power unless Otherwise Specified).

Project.	Name of Plant.	Maximum head (feet)	Horse power	
			Prime-movers installed	Total† proposed or possible
ARIZONA:				
Salt River	Roosevelt (a)	226	8,640	15,640
" "	So. Consolidated (b)	30	2,800	2,800
" "	Arizona Falls (c)	18	1,450	1,450
" "	Crosscut (d)	117	6,000	6,000
ARIZONA-CAL.:				
Yuma	Drop in Cal. Canal	9		1,000
"	Araz	25		7,700
CALIFORNIA:				
Orland		27		483
COLORADO:				
Grand Valley	Main Canal	44		3,600
Uncompahgre				10,000
IDAHO:				
Boise	Boise Dam (e)	30	2,550	2,550
"	Arrowrock Dam	230		17,000
"	Drops in canals	20-90		4,800
Minidoka	Minidoka Dam (f)	50	10,000	20,000
KANSAS:				
Garden City	Deerfield (steam) (g)		700	700
MONTANA:				
Flathead	Flathead River	60		360,000
"	Revais Creek	1000		26,000
Huntley	Main Canal drop (h)	34	286	600
MONTANA, N. D.:				
Lower Yellowstone	Lateral K. K. drop			290
NEVADA:				
Truckee-Carson	Lahontan ( )	120	1,800	6,000
" "	26-foot drop	26		2,000
NEW MEXICO-TEXAS:				
Rio Grande	Elephant Butte (steam) (j)		2,000	2,000
" "	" " (hydroelec)			10,000
NORTH DAKOTA:				
N. D. Pumping	Williston (steam) (k)		1,550	1,550
OREGON:				
Klamath	Various sites	22-88		9,700
Umatilla	Drainage outfall	28		145
UTAH:				
Strawberry Valley	Spanish Fork (l)	125	1,600	3,500
WASHINGTON:				
Yakima				
Sunnyside Unit	Drops in canals	20-88		1,800
Tieton Unit				3,250
Wapato Unit				9,000
Okanogan	Drop No. 1 (m)	105		250
"	" (n)	56		300
"	Salmon Creek	441		2,800
			39,376	532,908

*Power may be developed on other projects, but data not completed.

†Turbine capacity.

(a) Three 1680-h.p. and two 1800-h.p. turbines; five 1060-kw. generators.

(b) Two 1400-h.p. turbines direct connected; two 1000-kw. generators.

(c) Two 725 h.p. turbines direct connected; two 525-kw. generators.

(d) Six 1000-h.p. vertical tangential wheels; six 875-kw. generators.

(e) Three 850-h. p. turbines, direct connected; three 625-kw. generators.

(f) Five 2000-h. p. turbines, direct connected to five 1400-kw. generators.

(g) Two 350-h. p steam turbines and two 225-kw. generators.

(h) Two vertical turbines, direct connected to two 20-inch centrifugal pumps, capacity 28 second-feet.

(i) Two 900-h. p. turbines direct connected to two 625-kw. generators.

(j) Three 625-kw. steam turbine units.

(k) Two 300-kw. and one 500-kw. steam turbine units.

(l) Two horizontal 800-h. p. turbines and two 500-kw. generators.

(m) One 250-h. p. turbine; one 187-kw. generator.

(n) 300-h. p. turbine; one 187-kw. generator.

Other interesting developments are those in southern Idaho; the larger on Snake River near Minidoka, and the smaller on Boise River near the city of Boise. On several of the other projects, power plants have been constructed or are projected, notably in New Mexico at the large dam being built on the Rio Grande and in Utah on the Strawberry Valley project. In the State of Washington a number of small plants are under construction in connection with pumping extensions of the Yakima and Okanogan projects.

At each of the large storage dams, built by the Reclamation Service, there are opportunities for intermittent power, some of which will undoubtedly be utilized after this country has developed to a higher degree and markets are established.

The following extract from material for the forthcoming 13th Annual Report of the Reclamation Service gives in summarized form the capacity, output and construction costs for each of the more important power plants of the Service.

POWER PLANT DATA.

Project	Name of plant	Capacity kw.		Cost	Output kw-hr.	
		Rated	Safe observed		Sold	Used by Reclamation Service
ARIZONA,						
Salt River....	Roosevelt	5300	6000	*$642,654.23	9,336,802	2,932,230
	South Consolidated	2000	2000	162,123.05		
	Arizona Falls	1050	1000	109,500.73		
	Crosscut†	5250		incomplete		
IDAHO						
Minidoka	Minidoka	7000	7420	433,887.21	7,342,963	19,511,603
Boise.....	Boise	1875	2400	168,446.05	2,529,422	4,937,031
NEVADA,						
Truckee-Carson.....	Lahontan	1250	1450	85,437.63	219,544	2,110,127
UTAH,						
Strawberry, Valley	Spanish Fork	1000	1000	55,531.71	687,780	156,674
NEW MEXICO,						
Rio Grande...	Elephant Butte (steam)	1875	1875	136,491.83	14,825	3,275,285
N. DAKOTA						
Williston, ...	Williston (steam)	1150	1550	228,699.39	436,300	559,003
Totals ...		22500	24695	$2,022,771.83	20,567,636	33,841,953

*Exclusive of power canal and diversion dam $1,500,459.01. To the cost of this power plant will be added $33,000 to cover a 5000-kw. unit now being purchased, making a total cost of $725,654.23, and a total rated capacityof 10,300 kw.

†Not included in totals.

Arizona, Salt River Project. The power plants built in connection with the construction of the large Roosevelt dam and at several drops along the canals which distribute the water which has been stored behind the dam are among the most important built by the Reclamation Service. They illustrate the development of this somewhat peculiar type, the operation of which is necessarily made subsidiary or secondary to the use of water for irrigation. Here, however, where water is used throughout the year in irrigation the conditions to be met are less severe than those in Idaho, where the water is only used during the summer months.

*"The government has built the Roosevelt dam in the canyon of Salt River, 78 miles above Phoenix, to store over a million acre-feet of water for irrigation in the valley below. The dam is 280 feet high, affording a high head for a hydro-electric power plant. A plant was built below the dam to take advantage of this opportunity to furnish power for pumping underground water to irrigate additional land beyond the capacity of the gravity water supply. A 10-foot penstock through the dam operates machines under a variable head as the water is drawn out of the reservoir.

"The system also includes a power canal of 225 second-feet capacity and 19 miles long around the reservoir, making it possible to get the full head of the dam with the normal flow of the stream at all times. The power canal was built before the dam to furnish power for the construction of the dam itself, so that part of the original cost of the canal really belongs to the dam. The power house at present contains five machines capable of delivering about 5000 kilowatts, and it is intended to install a large machine this year that will bring the total output up to about 10,000 kilowatts. In the valley, the farmers have assessed themselves for money to build three other power plants in places where there is fall in the canal system, having a total capacity of 8000 kilowatts. When the plants now under way are completed the power system will represent an outlay of approximately $3,500,000, including the cost of the power canal. All of these plants are connected by a distributing system consisting mainly of 168 miles of steel tower, 45,000-volt transmission line and about 40 miles of 10,000-volt distributing line. The

*Abstract of article on the Salt River Valley power situation prepared by Mr. Wm. F. Cone and printed in the *Reclamation Record* for May, 1914.

surplus power over that required for irrigation is sold and the receipts go to reduce the cost of the project as charged against the land irrigated.

"Substations at Phoenix, Chandler, Glendale, Sacaton and Miami are distributing current for various uses. At Phoenix, all the lighting and electric power in the vicinity is supplied by the Government and is used for lighting the city, operating the street railway, ice plants, alfalfa mills and a cement mill. At Chandler, the power is used almost altogether for pumping. At Glendale, the Government supplies power for lighting the city of Glendale, operates several motors for different purposes and also takes care of a large pumping section just outside the project in what is known as the Marionette district. At Sacaton, power is furnished the Indian reservation for 10 irrigation pumping plants, for domestic water supply, and for lights at the Agency and School. At Miami the Inspiration Consolidated Copper Company is now putting in a large mill for handling low grade copper ore. This mill covers eight acres of land, all under one roof. The company will also operate a smelter, the mine machinery, hoists, lighting systems, compressors, and other devices by means of power from the Government system.

"In addition to the above-mentioned uses, the farmers in one section of the valley are now planning to put in a distributing system of their own, covering about 40 sections of land and bringing the power to their homes for pumping domestic water and doing general work around the farms, such as lighting and cooking."

Idaho, Boise Project. In connection with the construction of the Arrowrock dam, said to be the highest in the world, a power plant has been built on Boise River about 18 miles below the site, power being transmitted to the dam for use in construction. After the dam is built there will probably be installed at the reservoir itself a power plant capable of developing about 5000 h.p., which will be used in connection with the power plant now constructed at the lower point on the Boise River for supplying power for pumping water for irrigation and for commercial purposes.

*Idaho, Minidoka Project.** This is one of the largest and most interesting developments of hydroelectric power made by the

*See detailed statement by Barry Dibble in *Journal of Electricity, Power, and Gas*, July 11, 1914.

Reclamation Service. The power house is at a dam which was constructed across Snake River for the purpose of diverting water by gravity to 70,000 acres. This dam has a maximum height of 86 feet and a length of 937 feet. In addition there is a concrete spillway about half a mile in length on which the water can be controlled by flashboards, thus adding needed storage. The drainage area above this diversion dam is 22,600 square miles. The normal floods occur in June and usually reach a peak of some 30,000 to 40,000 second-feet. In low-water stage, which follows soon after in July and August, the river drops to 2000 second-feet, although from 2500 to 3000 is a usual minimum.

At all times water must pass this dam, as there are prior water rights to the amount of 3400 second-feet, so that all of the flow up to this amount during the irrigation season must be passed for the use of the lands below if needed by them. This has necessitated the development of storage on the head-waters of Snake River in Wyoming, about 300 miles above the Minidoka dam. This storage is created at Jackson Lake in Wyoming, where by building a low dam an available capacity of 380,000 acre-feet has been obtained, this being in addition to the 53,500 acre-feet which can be held in Lake Walcott immediately above the Minidoka dam and power house.

On the north side of the river, water is diverted by gravity to irrigate about 70,000 acres of land. On the south side, the water diverted by the dam is used mainly to supply lands which lie above the gravity supply and to which the water must be lifted by pumping, utilizing for this purpose the power developed at the dam through the use of the water which must be passed down the river for the lands farther down the stream.

The power is developed under a head of 46 feet and the plant consists of five principal units each having a capacity of 2000 h.p. in the water turbine. These turbines drive electric generators which have a normal capacity of 1200 kw. each and which under a high head have delivered as much as 1600 kw. each.

The storage lake immediately above the dam, known as Lake Walcott, covers 10,000 acres, and is used in summer time as an auxiliary storage in which the water can be raised five feet above the spillway crest of the dam by means of flashboards. When the lake is thus raised additional head is made available at the power house to increase the capacity of the plant. Water is taken from the lake to the turbines through 10-ft. penstocks,

each of which carries approximately 500 cu. ft. per second, when operating at full capacity.

Electric energy is generated at 2200 volts, carried by cables through fiber conduits to air-cooled transformers, which raise voltage to 33,000 volts for transmission.

All the wiring and switching beyond the transformers is in duplicate, and all the way through the greatest precautions are taken to prevent any accident. The variation of load on the power house is extreme, the greatest demand being during the heat of the summer when water is needed for irrigation. Great fluctuations are caused by occasional rains which lessen the irrigation demand.

During 1913, the output of the station reached 28,265,287 kw-hr., with an observed peak of 7420 kw., making the annual load factor nearly 40 per cent. The annual cost of operation and maintenance amounted to practically $16,000, or less than 0.07 cent per kw-hr., independent of fixed charges. Including fixed charges, general expense and depreciation, cost in 1913 was 0.126 cent per kw-hr.

From the power house, two transmission lines extend over the project, crossing the river and uniting so as to form a loop over which the current can be supplied. There are about 62 miles of 30,000-volt lines and over 20 miles of 2200-volt lines, supplemented by distribution systems in the towns and owned directly by settlers. The annual cost of operating and maintaining the high-tension lines is about $40 per mile.

The pumping stations which supply water to approximately 48,000 acres of land are the largest which have been built for irrigation purposes. It is believed that the pumping stations for the city of New Orleans which are used in the case of severe rainstorms to remove the storm water from the sewers of the city, are the only pumping stations in the United States which have a larger capacity than those on the Minidoka project. The station buildings, which are of concrete, contain transformers for lowering the voltage from 30,000 to 2200, and also house the motors and pumps.

There are ten pumps which were originally of 125 second-feet capacity, each driven by a 600-h.p. motor, and two 75-second-foot pumps driven by 360-h.p. motors. At each station the lift is approximately 30 ft., so that the lift of the third canal is nearly 90 ft. above the gravity supply.

Approximately 127,000 acre-feet of water were pumped during

the season of 1913, and of this, 17 per cent were used on the 30-ft. level, 36 per cent on the 60-ft. level and 47 per cent, or nearly one-half, on the 90-ft. level.

The average lift for the season was 68.3 ft. The power required was nearly 16,000,000 kw-hr. with a peak of 6550 kw., corresponding to a load factor of 27.7 per cent. The cost of operating and maintaining the three stations was $13,000, exclusive of the fixed charge and of the cost of power, or a trifle more than 10 cents per acre lifted the average height. The cost of operation and maintenance of the canal system amounts to an additional 75 cents per acre.

There has been very heavy demand on the pumping stations for a week or ten days in the middle of the summer and at this time all of the machinery has been pushed to its fullest capacity. Efforts are being made, however, to arrange by rotation of delivery of water to spread the demand over a longer period without hardship to the farmers and avoid the excessive demands for the very short period.

During the winter of 1913-14, alterations have been made in the runners of several of the large pumps and recent tests indicate that the changes will increase the capacity from 125 to 165 second-feet and improve the efficiency of the pumps from 72 per cent to over 80 per cent.

North Dakota, Williston Pumping Plant. This plant, although relatively small in size, is of peculiar interest because of the fact that the government owns and operates the coal mines which supply the fuel, this being dug immediately adjacent to the power house, and the coal carried immediately from the mine through crushers into the hoppers which supply the furnaces. Burned there, the steam generated is used in turbines, which in turn convert the energy into electric power, which is transmitted from the power house down to the Mississippi River, is carried out onto barges which contain pumps which in turn lift the water from the river to settling basins on the land, from which it can flow by gravity back to the power house, be there picked up by suitable pumps, raising it about 30 ft., from which level it flows to the lands to be irrigated.

In addition to the power which is used during the summer to pump water for irrigation, there has been provided an all-the-year-round load by making arrangements with the City of Williston for sale of power for lighting the city and for other purposes. It has been found that a government bureau is not the ideal form of organization to handle economically the retailing of

electrical power to small consumers. Therefore, the policy has been adopted of aiding the farmers and local people to form mutual companies to build their own lines to connect with the government system, install their own house transformers, and handle the retailing of the power.

Conclusion. In what has been stated above, sufficient detail has been given to illustrate the general character and extent of the works being built by the government through the Reclamation Service and to indicate the policy which up to the present time has been found advantageous. A certain amount of experience has been acquired in this class of development work and the demonstration made that it is possible for the government to build and operate works at a cost comparable to the outlay by ordinary corporations. The results, therefore, have peculiar interest to the citizens of the country as showing what may be done and also the difficulties to be avoided in governmental operations of this kind where the question of profit and interest on the investment is not considered, but rather the general benefit in upbuilding a community under pioneer conditions. When these communities are upon their feet, it is the intent of the law that all of these works be turned over to the landowners and be maintained by them at their own expense, under such regulations as may be desirable at the time. It is to be noted that these landowners are to pay for the actual cost of the work in annual installments which, under the terms of the act of August 13, 1914, have been extended from 10 years to 20 years, without interest on the deferred payments.

The employes of the Government engaged in the construction and operation of these works at all times stand ready to assist the small subsidiary companies or organizations of farmers and water users to build their own lines, to make repairs, and in fact to aid them in every way possible, usually taking the initiative in urging the farmers to find new uses for power. So that ultimately, when the hydroelectric works or big power plants are turned over to the organizations of farmers they will have had experience adequate to operate them through the employment of competent electricians. At present the rural lines cannot be considered a profitable investment from a power company's standpoint. However, they enhance the value of the farms which are reached by the lines and the material saving to the farmers which comes from use of electricity makes the investment a good one from the farmers' standpoint.

DISCUSSION ON "ELECTRICAL FEATURES OF THE UNITED STATES RECLAMATION SERVICE" (NEWELL), PHILADELPHIA, PA., OCTOBER 12, 1914.

Paul Spencer: Upon hearing the paper read, I was struck with the advantages of having someone supply you with money without interest charges, and being able to make contracts on which you could shut off power whenever you did not have it, or did not wish to supply it. Under those circumstances, I can understand that you might be able to sell your surplus electricity at the price stated. The low rates can only be considered as due to those extremely peculiar conditions.

Ralph W. Pope: It is not quite true that the cost of installation is given to the owners of the land, or that they do not pay the cost. That is all figured out, and included in the price that they pay for the land, and it is expected that the installation will be paid for by the consumers in the course of twenty years. As to the low rate, there is absolutely no use for the power in winter. The intent of the irrigation plant is to supply water for irrigation, and no pumping is required during those months when the low rate is given. It is simply a question of competing with coal, for heating, and this is possible where coal is $7 a ton.

I had occasion to inquire about this matter of taking up land, and the replies I got were conflicting. One question that I asked a man, was whether they found men who were willing to take up these small tracts and pay the price, whether or not they were farmers who were accustomed to operating small farms. He said that was one of the difficulties that they had to contend with, that they did not find people ready to take up the land under those conditions. Another man that I met further on, said that where he was, they had had no difficulty of that kind, that there was no trouble at all in finding people who were willing to settle under those conditions. So, there you have the two statements, probably one coming from one part of the country, and the other from another part.

It is certainly a very interesting subject, and since I have learned more about irrigation, I realize that it might have been used in our eastern States to great advantage, and we would have less growling about a drought, such as exists now in many parts, if farmers had utilized the water which is available for such purpose. Of course, this is not always the case, because we do not have the snow-capped mountains in the East to furnish water through the action of the sun, so that the conditions are somewhat different.

J. E. Kershner: I was looking over the table on page 1611, and, a little contrary to a previous speaker, I cannot say that I was struck with the cheapness of the power, except, perhaps, in two instances—0.268 cent and 0.126 cent per kw-hr. If you except those two cases, we can buy wholesale power cheaper

than any of the other figures, from Pennsylvania water power companies.

P. M. Lincoln: The extremely low rate for heating, given in the table on page 1613, is possible simply because during the winter time they have no other use for the power, and the only market for their power is for heating purposes. The load factors are given on page 1611. Those prices apply for the load factors actually given. You will notice that where the load factors are high, the prices are low, and where the load factors are low, the prices are high.

H. A. Hornor: There is one fallacy spoken of in the paper that we all know very well, but it seems to me that it is important from the standpoint that the public does not seem to understand it. I refer to the question of transformer losses. I have heard it stated by an engineer of one of the most efficient central stations in the eastern part of our country, that the coal consumption on Sunday about equalled the normal daily coal consumption during the week, due simply to transformer losses. I think the public fails to appreciate that the central station has to carry a transformer load in order to supply its customers with reliable power.

Vladimir Karapetoff: Mr. Newell in his paper does not claim to bring out anything new from an engineering point of view. On the contrary, he emphasizes the fact that the construction used is standard as much as possible. Nor is the paper remarkable for the size of the plants or the hydraulic head used. We have a great many plants in comparison with which the plants he describes are mere dwarfs. But the paper is of great interest because it gives examples of successful hydroelectric work done by our government. Those of us, who, like myself, are believers in government ownership and operation of public utilities, welcome a paper of this kind, because it furnishes us with valuable material for our argument. We have very little inkling of the successful engineering work done by the government. This afternoon we listened to an account of the highly successful work done by the Navy Department in cooperation with private concerns. I welcome Mr. Newell's paper as showing that there is no reason why the government should not engage in a hydroelectric project and bring it to a successful end.

There are just two points about which I would like to ask. On page 1611 the cost in cents per kw-hr. is given. Is it not rather misleading, to give the cost per kw-hr. in a hydroelectric station? The first plant, for instance, operates at an annual load factor of 12.7 per cent, and the cost in cents per kw-hr. is 0.81. The plant could furnish, say, five or six times that amount of power, with very slight increase of expense for additional personnel, and the cost in cents per kw-hr. would be, say, one-fifth of that given. In other words, it seems to me that the last column does not really give the cost, unless it is always

quoted in connection with the annual load factor. There ought to be some other basis for comparison. Of course, one basis is the cost of the original construction, per kilowatt capacity.

Another point is this: Some years ago I was asked to investigate into the possibility of certain electrochemical processes in this country that require cheap power, and particularly one of fixation of atmospheric nitrogen, a problem which appeals so much to our imagination. At that time I could not find any place where power could be purchased at a figure that would warrant such an installation. After reading these wonderful figures of cost, I should like to ask those who, like Dr. Hering, understand about electrochemical processes, if nitrogen fixation, or some other fertilizer process, could not be run intermittently during the winter months in connection with one of these plants?

Carl Hering: It seems to me that answers itself, provided such a process can be interrupted; in fact, at a recent meeting of another society, I cited that very case as one in which power could be "stored" more cheaply and better than it can be stored as water in reservoirs. I refer to those electrochemical plants which can be run when the water power exists, and can be shut off when it does not exist. In that way the product can be produced while the water is flowing, and can be sold at one's leisure, which is in effect a process of storing the energy. There is no doubt that this can be done with some electrochemical processes, but not with all of them.

In connection with what Prof. Kershner said, I notice at another place in the same table, on page 1611, that these costs are stated to be those at the switchboard, and not for power delivered to the premises. It is one thing to generate power, and another thing to transmit it and deliver it; the cost of transmission is sometimes great. One would have to run his own lines to the switchboard, to use the power at these rates. If the cost of distribution is added to the figures in the lower part of the table, the energy is by no means cheap.

Mr. Bender: I would like to ask, also, in connection with those figures, if interest is included in those costs. That would be another item to be taken into account.

P. M. Lincoln: I am not sure of that, but I think interest is included, but at a very low rate, a rate at which the government can borrow money.

H. Goodwin, Jr.: Mention has been made of the use of water for irrigation in the orange orchards in Southern California, and it might be of interest to try to get a little nearer to the point of view of the men operating those orange groves. Two years ago I was at Santa Paula, about 100 miles north of Los Angeles, at the oldest lemon grove in Southern California, which is now growing many oranges, too. They own the water rights of a small stream which supplies sufficient water for irrigation all through the irrigation season. The grade at which the

water reaches the grove is the highest of the level section, but above that are many acres on a steep hill which were used only for hay. (Their hay is a mixture of barley and oats, and not our timothy and clover). There was so much money in oranges that they were considering putting about 50 acres of this land into oranges. To do that they would have to pump water to the top (by electric power, of course).

At the rate they receive for such purposes it was found that it would cost them $18 a day for pumping water up over this hill of 50 acres. That was no hindrance at all to them. They went right ahead with the proposition. Eighteen dollars a day is nothing at all to them. But if you tell a farmer here in the east to spend $18 a day for pumping water over his land, so as to double his output, he will tell you you are crazy.

There is another interesting point about the way they use the power. One very large item of expense of which Mr. Hornor has spoken is transformer expense. They avoid this by using 2400 volts just as we would use 110 volts here. All the pumps are 2400 volts. They run the overhead lines on ordinary D.G. glass insulators, come into a little shack through porcelain tubes, erect some current transformers and a meter, put a couple of knobs on the ceiling, and drop down to the motor in the center of the floor. This wiring does not cost them much over $20 or $25, which is a decidedly different proposition from our transformer installation, and other work we have to do in this section. Yet I could not find any case of death by electrocution of any of the men working around these groves.

The point of view of the Southern Californian is so different from our own in regard to spending money on farms, that it should be of interest to us to look at things occasionally from that viewpoint.

F. H. Newell (by letter): The above discussion indicates that the object of this paper has been correctly understood and that it is necessary only to answer one or two questions.

With reference to the taking up the reclaimed land, there has been relatively little difficulty or delay in this, as the public lands are practically given away under condition that the cost of bringing water to these lands, including the expenditures for the hydroelectric power plants and other accessories, is repaid by the land owner within 20 years. The time for repayment was originally set at 10 years, but by Act of Congress of August 13, 1914, it was extended without interest to 20 years. Thus the land owners are called upon to pay an average of only 5 per cent on the principal, not interest, for 20 years and then all payments cease, except for operation and maintenance. The amount paid, however, during the first few years is less than 5 per cent, but during the later years of the 20-year period is as high as 7 per cent, being adjusted so as to make complete payment of construction cost within the 20-year period.

In regard to the cost of lands which have passed into private

ownership, the prices set on these have been high, but the inflation has practically ceased, and lands irrigated by the government are now being held at more moderate prices than in the past few years. The difficulty has not been so much that of disposing of the land as in getting it utilized to the best advantage after it has passed into the hands of homestead entrymen or purchasers. The lack of capital and high interest charged on borrowed money has delayed development, but with the gradual growth of the country and increase of small industries made possible by cheap power, there is a steady improvement in agricultural conditions.

One of the striking needs, as pointed out in the above discussion, is that of some method of storing this cheap power, one which may possibly be brought about by electrochemical processes. Here is a field for invention which it is hoped will be entered upon at an early date.

The experience which is being acquired in construction, operation and maintenance by the government of works of this character cannot fail to be of value, particularly at the present time when there is general agitation for enlargement of governmental functions. This paper will have fulfilled its purpose if it has attracted attention to some of the opportunities and limitations of such governmental undertakings.

Presented at the 301st Meeting of the American Institute of Electrical Engineers, New York, November 13, 1914.

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THE CORONA PRODUCED BY CONTINUOUS POTENTIALS

BY STANLEY P. FARWELL

ABSTRACT OF PAPER

This paper deals with an experimental investigation of the corona around small wires as produced by continuous potentials up to 15,000 volts. The continuous potentials were obtained from a series of 500-volt generators.

The wire and coaxial cylinder method was employed for a number of experiments. Critical voltages and characteristic potential difference and current curves were obtained for different sized wires. The effect of lowering the pressure in the cylinder upon appearance of corona, critical voltage, and current, was studied. It was found that the appearance of the corona depended upon the polarity of the wire; positive polarity gave continuous glow, while discontinuous beaded appearance characterized the negative corona, the number of beads being a function of the pressure and the potential difference for a given size wire. A short arc in series affected the nature of the discharge by superimposing a high-frequency current upon the direct current. Characteristic curves were taken to show the effect of varying pressure, moisture and temperature. An increase of pressure inside the closed cylinder was produced by the application of a potential difference greater than the critical value; this increase is due to ionization.

Corona in the case of parallel wires was studied by taking characteristic curves and exploring the field. Field exploration showed anode fall of potential greater than cathode. Corona accompanied by mechanical effects on wires: deflection on both wires and circular vibration of positive wire.

THE DIRECT-CURRENT CORONA

IN alternating-current transmission lines at very high voltages a loss occurs by dissipation of power into the air. This is accompanied by luminosity of the air surrounding the conductors, and to this glow the name "corona" has been given. Loss begins at some critical voltage, depending on the size and spacing of the conductors, etc., and increases very rapidly above this voltage. This corona effect is of considerable importance, as it involves a power loss of some magnitude on long lines, and it has been studied by Steinmetz, Scott, Ryan, Mershon, Jona, Peek, Whitehead and others.

The corresponding direct-current case, although not of such immediate importance, is yet of considerable interest in view

of the high-tension direct-current developments on the continent of Europe. The only work of much importance along this line has been done by Watson[1] and Schaffers.[2] Watson has carried out a number of tests of wires strung axially along a cylindrical tube and also on two parallel wires out-of-doors. The wires used were of various diameters between 0.70 mm. and 12.76 mm. The source of power was an influence machine of special design and large output which would give any potential required up to 70,000 volts.

The electric stress at the surface of a wire subjected to electric potential is as follows:

Wire in cylinder:

$$R_{max.} = \frac{V}{a \log_e \frac{b}{a}}$$

Two parallel wires:

$$R_{max.} = \frac{V}{2_a \log_e \frac{d}{a}} \left(1 + \frac{a}{d}\right)$$

where V = potential difference between wires, or between wire and cylinder,
a = radius of wire,
d = distance apart of wires,
b = radius of cylinder.

Of these formulas, the first is exact, while the second is only approximate, but is very nearly correct for all ordinary cases where a is small compared to d, and the wires are well above the earth.

The value R_{max} in the above formulas is called by some writers the "critical surface intensity" and is extensively used in expressing the results of tests. It has been well established by Watson, Whitehead and others that this critical surface intensity increases very greatly as the radius of the wire decreases. A comparison made by Whitehead of his results for this intensity in the case of alternating potentials with the similar values deduced by Watson for continuous potentials, shows that for a given size of wire it requires the same voltage to produce corona in both cases, if the maximum value of the alternating potential be used.

1. Watson, *Electrician*, London, Vol. 63, 1909, p. 828; Vol. 64, 1909-10, pp. 707 and 776.
2. Schaffers, *Comptes Rendus*, July 1913, p. 203.

For the case of a wire in a cylinder Watson found some differences between the case when the wire was positive to the cylinder and when it was negative to it, these differences occurring both in the appearance of the corona and in the measurements relating to it.

The article by Schaffers referred to above, gives the results of a study of the ionization in cylindrical fields, using wires of various diameters ranging from 0.0006 cm. to 0.70 cm. in tubes ranging from 0.70 cm. to 11.7 cm. in diameter. He says nothing of the source of potential used or of the appearance of the coronas. He finds that for the larger size wires the positive corona appears at a lower voltage than the negative and that for the smaller sizes, the reverse is true, the radius 0.01 cm. separating these two regions. Another conclusion reached by this investigator is that the nature of the material of the wire is without effect upon the coronal voltage, at least if the wires are not very fine.

When this investigation was undertaken, there was no physical theory advanced which explained the phenomena observed. During the progress of this work, however, two theories were published, one by Bergen Davis (TRANS. A.I.E.E., this volume, part 1, p. 589) the other by J. E. Townsend (*Phil. Mag.*, May, 1914,) which try to explain the phenomena by ionization through collision. Both theories neglect the influence of light and a number of phenomena that have been discovered in the present investigation.

In view of the scarcity of certain data as to the corona at continuous potentials, the object of the work described in this paper has been to extend our experimental knowledge in this direction.

DETAILS OF EXPERIMENTAL APPARATUS

The source of the continuous potentials employed was a battery of small continuous-current generators connected in series. There were thirty of these, each rated as follows: Amperes, 0.5; watts, 250; speed 1700; volts, 500; shunt-wound. The potential available, then, was 15,000 volts when the machines were run at normal voltage.

These generators were arranged in two sets, one of twenty machines and the other of ten. The generators were self-excited and could be put into service by closing a small knife-switch in each field circuit. Voltage control was obtained in this manner and by controlling the speed of the set by field

control of the driving motor. A fine adjustment of voltage was obtained by means of a rheostat in the field circuit of one of the generators. The series connection between the machines was permanent.

The diagram of connections in Fig. 1 is self-explanatory. The apparatus labeled "Short Arc" consists of an air gap between the head of a tack and a copper wire. This spark

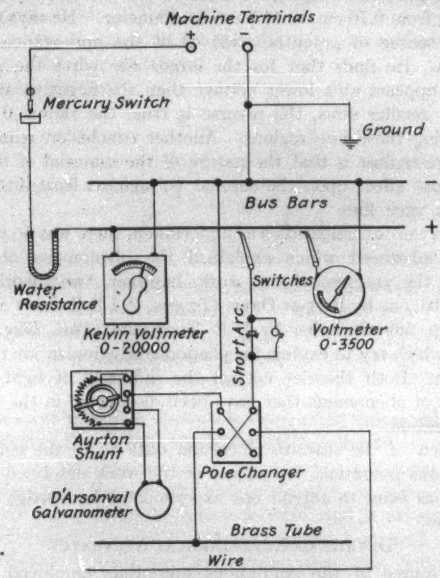


FIG. 1—DIAGRAM OF CONNECTIONS

gap could be cut out of the circuit by closing a shunt around it. Special care was taken in setting up the apparatus to thoroughly insulate it from the ground, except that the negative terminal of the generating apparatus was grounded, in order to minimize the danger from shock.

The voltage between the busbars and hence, with sufficient accuracy, the difference of potential impressed upon the corona

apparatus, was measured by means of electrostatic voltmeters. For the lower ranges an instrument was employed having a range of 3500 volts and accurate to within one per cent. This conclusion was reached by comparing its indications with those obtained by adding the voltages of the machines used, as given by a 750-volt direct-current portable voltmeter which had been carefully calibrated.

For the measurements of the higher differences of potential a vertical type Kelvin electrostatic voltmeter was used. This instrument had three ranges, of 5000, 10,000, and 20,000 volts, which could be secured by hanging the proper weights from a lug at the bottom of the needle. Only the 10,000 and 20,000 ranges were used. The lower part of the 10,000 range was calibrated by the same method as for the lower range voltmeter, as well as by measuring the voltages indicated by the portable voltmeter when a high resistance was inserted in series with it. This high resistance was made of a U-tube containing alcohol into which two platinum wires dipped. This resistance was kept from heating by immersing it in a mixture of ice and water. Under these conditions the resistance was very constant for the small currents used.

The higher ranges of this voltmeter were calibrated by reference to an attracted disk electrometer. This instrument had a disk 5.5 cm. in diameter. The aperture of the guard-ring was 5.9 cm. in diameter and the outside diameter of the guard ring was 16.0 cm. A separation of 1.5 cm. was used between the disk and the lower plate.

Due to the non-uniformity of the field at the edge of the disk, an edge correction must be applied to the indications of the electrometer. This edge correction is treated by Maxwell in Vol. 1 of his "Electricity and Magnetism" and the conclusions reached are briefly as follows:

Let

R = radius of disk
R' = radius of aperture
D = distance between plates
A = effective area of disk
$\alpha = 0.220635\ (R'-R)$
W = wt. in grams to balance.

Then

$$V = D\sqrt{\frac{8\,\pi\,g\,W}{A}}$$

where

$$A = \frac{1}{2}\pi\left[R^2 + R'^2 - (R'^2 - R^2)\frac{\alpha}{D+\alpha}\right]$$

Using the numerical constants of the instrument as given above, there results:

$$\alpha = 0.044$$
$$A = 25.474 \text{ sq. cm.}$$

We may write $V = k\sqrt{W}$, where k is the constant

$$D\sqrt{\frac{8\pi g}{A}}$$

Then $k = 13{,}992.3$. By a similar series of operations we find that for plates 1 cm. apart, $k = 9357.6$.

By use of the value $k = 14{,}000$, which is nearly enough correct, the values of W to balance for different voltages were calculated, and a test run to determine how closely these values checked with the actual weights required for a balance when the voltages indicated by the electrostatic voltmeter were impressed. A consideration of these figures with due regard to the accuracy of the determinations led to the final calibration.

D'Arsonval galvanometers were used to measure the discharge currents obtained with the various pieces of corona apparatus. Most of the characteristic curves were taken with a very sensitive galvanometer which had a small coil, a resistance with connecting wires of 326.0 ohms, and was practically dead-beat. For the later moisture and pressure determinations which extended over some days, a less sensitive instrument was used. This had a heavier coil, a resistance with connecting wires of 849.5 ohms and a period of six seconds. Its figure of merit was about five times that of the first instrument.

The figure of merit of these galvanometers was determined from time to time, using accurate resistances of high value and as a source of e.m.f. either a dry cell or a standard cell. In the case of the dry cell, its e.m.f. was determined from the indications of an accurate laboratory standard voltmeter. An Ayrton universal shunt was used in connection with the galvanometer. This shunt box had five coils connected between contact points.

Preliminary Experiments

When this work was first undertaken, it was not apparent from the limited literature of the subject what one might expect in the way of coronal phenomena which might be produced by potentials up to the total voltage of the generating sets, namely 15,000 volts. No glow could be obtained between flat plates; only an arc. Then an investigation was begun to find out what kind of terminals would have corona produced between them by the comparatively low voltage available.

A brass rod, 0.637 mm. in diameter, was located axially along a tube 4.45 cm. in diameter and the full voltage of the sets was impressed. No effect was visible. Then provision was made for exhausting the tube, and at about one-quarter atmosphere a discharge took place. This took the form of brilliant radial purple arcs terminating in bright blue "stars" on the walls of the tube. These arcs were in constant motion around the wire and along the tube and reminded one of a pinwheel. A fairly large size wire was substituted for the rod and still no corona could be obtained at atmospheric pressure.

Recourse was next had to large influence machines. It was known that the silent discharge between points was of the same nature as the corona between wires and it was reasoned that if the e.m.f. of an influence machine were impressed between small parallel wires, a discharge would take place between them. Two bare No. 40 wires were stretched parallel to one another and a few centimeters apart, and a silent discharge was found to take place between them. The appearance of the discharge was at once seen to depend upon the polarity. The discharge was discontinuous, small brushes on the negative wire corresponding to sections of uniform glow on the positive wire. The brushes were in a more or less constant movement back and forth along a short path, but they appeared to be more or less evenly spaced along the wires. It was also noticed that the wires vibrated and that the negative wire bowed in toward the positive, which bowed away from the negative. It was as though a wind were blowing across the wires.

Another experiment was tried with a No. 40 wire above a sheet of tinfoil. With this arrangement and wire positive, a continuous glow appeared along the wire, while when the wire was negative the discontinuous brush discharge appeared again. Vibrations were also noticed with this apparatus.

A mandolin steel "*E*" string, 0.24 mm. in diameter, was

strung along the axis of a brass tube of about 3 cm. diameter and the wire and tube were connected to opposite polarities of the influence machine. If the wire was positive, a continuous bluish glow of markedly uniform appearance appeared along the wire. When the wire was negative, the discharge was in constant movement and seemed to consist of countless purple streamers or brushes. There seemed to be no appearance of regularity of spacing of isolated brushes.

When these tests were run it was noticed that the main discharge knobs on the machine could be moved together until they almost touched before a spark would pass. This indicated that the difference of potential between the parallel wires, for example, could not be very high, not over 10,000 volts perhaps. This fact suggested that similar discharges with small wires should be produced by the continuous potentials from the generating sets. So the experiments were carried out again and it was found that the same effects were produced by the generators.

The crude tube apparatus was fastened to a board by means of nails driven into the wood and bearing against the wall of the tube. Connection was made to the tube by wrapping a wire around one of these wires. This wire became loose and separated 0.01 inch or so from the tube. The consequence was that a short arc was established between the wire and the tube. The presence of the arc caused a marked difference in the character of the positive discharge. With a potential difference of about 8000 volts and the wire positive to the tube, a very active discharge took place between the wire and tube. The whole tube appeared filled with a bluish glow particularly brilliant around the wire, where an uneven effect was apparent, resembling a brush discharge. The discharge was unstable and variations in the arc produced marked variations on the discharge. After the bluish glow had continued for some minutes, the nature of the discharge became suddenly different. Purple arcs appeared, of much the same nature as those mentioned above in connection with the discharge from a rod at low pressure. After a while the discharge would resume its former character and then the process would repeat. The arc between the nail and tube appeared bluer while the whirligig discharge was going on. A small wire was slipped in to bridge the gap between nail and tube and then the discharge became merely a faint blue glow of a uniform nature, apparent only in

the immediate vicinity of the wire. With the gap closed, the wire negative, an entirely different discharge took place. Small purple brush-like discharges were clustered irregularly along and around the wire and these held their positions fairly constant. When the arc was again introduced, the discharge appeared somewhat dimmer, although keeping its nature about the same, as far as could be seen by looking from the end of the tube.

Characteristic Curves at Atmospheric Pressure

In order to study the influence of diameter of wire upon critical voltage and discharge current, a number of different sizes of bare wire ranging from No. 40 to No. 10, copper, were obtained from the manufacturers and an apparatus was constructed in which the tests could be carried out. This apparatus consists essentially of a brass tube 4.45 cm. in internal diameter, well insulated from its support and provided with means for accurately and tightly stretching a wire along its axis. The tube was provided with a small branch tube through which the air could be exhausted. The centering of the wire was accomplished by passing it over hard-rubber bridges in which there were notches axially located with respect to the tube and stretching it tightly by means of a mandolin tension-head. In order to limit definitely the length of the wire from which a discharge could take place, glass plates were sealed to the ends of the tube and the wire passed through holes in them about 3 mm. in diameter. For most of the characteristic voltage-current curves, the exhaust tube and the holes in the plates were left open and the air in the tube had the same constitution as that in the room, at least at the beginning of the test.

In order to make sure that no current would flow through the apparatus except that through the air, a small wire was arranged so that the tube was in the same condition as for a test except that none of the wire extended inside of the cylinder. Then differences of potential were applied up to 10,000 volts and the currents measured. It was found that even at the highest voltage the current was insignificant.

For the first wires tested, a start was made at a low voltage and the currents taken by small increments on the way up. It was soon found that the current flowing was negligible until the voltage approached that necessary for a visible glow, and therefore later tests were started at a voltage somewhere near

the critical voltage. For each voltage the deflection of the galvanometer was read for both polarities of the wire.

When the wire was positive and the voltage neared that necessary to cause a visible glow, a very marked jump of the deflection would occur and a further increase of the voltage caused the current to increase very rapidly. The voltage at which this sudden increase of the deflection took place was called the "critical voltage." "Visible glow" was taken to mean the first appearance of light in the case of the wire positive. This glow appeared suddenly for all but the smallest wires, in which case the dimness of the glow made it hard to tell just where the limit of visibility was.

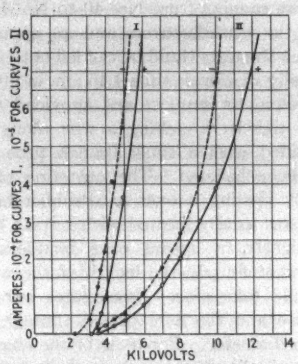


FIG. 2—CHARACTERISTIC: SILVER WIRE 0.037 MM. DIAMETER

Tube 4.45 cm. diameter, 25 cm. long; temperature 26.7 deg. cent.; relative humidity 45.3 per cent; barometric pressure 736.48 mm.

As has been noted, the presence of dirt or dust particles on the wire, when negative, has a marked effect upon the discharge. Often a spot or two on the wire would glow long before the wire as a whole was luminous. Due to this fact there is no definite critical voltage as in the case of the positive polarity, for the initial jump of the deflection is much a matter of chance. But as the voltage is increased, there occurs a critical voltage at which a flickering glow can be seen along the wire preliminary to the spreading of the discharge from a few spots over the whole wire. This phenomenon occurs at a definite voltage for a given size wire and it is this voltage which is given in the tables under "visible glow" for the negative polarity.

Readings of wet and dry bulb thermometers and an aneroid barometer were taken for each test and the per cent relative humidity was calculated. The barometer was checked from time to time by reference to a very accurate mercurial barometer.

The silver wire used in these tests was really silver wire with a platinum core, known as "Wollaston" wire. This wire was used both in its original state, diameter 0.0517 mm., and with some of the silver dissolved off, giving wires of average diameter 0.027 and 0.037 mm.

The tungsten wire was of the sort used in 25-watt lamps.

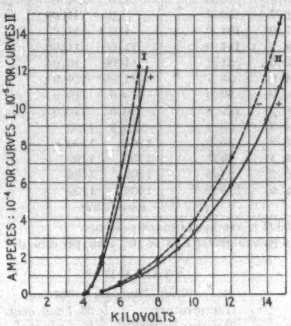


FIG. 3—CHARACTERISTIC: NO. 40 B. & S. COPPER WIRE, 0.077 MM. DIAMETER

Tube 4.45 cm. diameter, 25 cm. long; temperature 25 deg. cent.; relative humidity 41.6 per cent; barometric pressure 745.3 mm.

The diameters of the very small wires were obtained by the use of a microscope fitted with a stage ruled with parallel lines.

VARIATION OF CRITICAL VOLTAGE AND GLOW VOLTAGE

Tables I and II give data on critical voltages and the voltages required to produce continuous visible glow for wires of diameters ranging from 0.027 mm. up to 1.28 mm., and are plotted in Fig. 2. Similar tables for Figs. 3, 4 and 5 are omitted. A study of these data showed the following facts:

a. For the smaller sizes, the critical voltage is considerably lower than the glow voltage, showing that quite a current exists before a luminous discharge occurs. This applies for wire positive.

TABLE I

Silver Wire—Diameter 0.027 mm.
Temperature 26.6 deg. cent.
Relative Humidity 54.4 per cent.
Barometric Pressure 741.55 mm.

	+	—
Critical Voltage	2100	1880
Visible Glow	2720	2520

Potential Difference	Galv. defl. in mm. +	Galv. defl. in mm. —	Shunt factor +	Shunt factor —	Current in 10^{-4} amp. +	Current in 10^{-4} amp. —
1750	1.1	1.2	1.0	1.0	0.000032	0.000035
2100	25.0	60.0	1.0	1.0	0.00072	0.00173
2500	66.7	50.7	1.0	11.09	0.00192	0.0162
2800	137.0	101.0	1.0	11.09	0.00394	0.0322
3000	18.2	147.0	11.09	11.09	0.0058	0.0469
3200	33.0	21.1	11.09	110.9	0.0105	0.0674
3500	101.0	36.7	11.09	110.9	0.0322	0.117
3860	30.9	69.0	110.9	110.9	0.0986	0.220
4350	66.2	122.8	110.9	110.9	0.212	0.392
4920	114.8	18.4	110.9	1109	0.335	0.588
5950	23.9	35.2	1109	1109	0.763	1.12
7000	39.4	56.7	1109	1109	1.26	1.81
8000	60.7	87.5	1109	1109	1.94	2.80
9100	82.0	113.0	1109	1109	2.62	3.61
			wire broke			

Wire rough: 0.027 is average of many readings.
Figure of merit of galvanometer 2.88×10^{-9} amp. per mm. defl.

TABLE II

Silver Wire—Diameter 0.037 mm.
Temperature 26.7 deg. cent.
Relative Humidity 45.3 per cent.
Barometric Pressure 736.48 mm.

	+	—
Critical Voltage	3100	2200
Visible Glow	3380	3230

Potential Difference	Galv. defl. in mm. +	Galv. defl. in mm. —	Shunt factor. +	Shunt factor. —	Current in 10^{-4} amp. +	Current in 10^{-4} amp. —
2150	1.5	2.1	1.0	1.00	0.00004	0.00006
3000	4.0	117.0	1.0	11.09	0.00011	0.0374
3500	85.7	39.3	11.09	110.9	0.0274	0.126
3650	117.7	53.3	11.09	110.9	0.0565	0.170
3860	29.0	68.8	110.9	110.9	0.0926	0.220
4350	68.8	127.7	110.9	110.9	0.220	0.407
4920	114.3	172.7	110.9	110.9	0.365	0.551
5950	242.0	34.4	110.9	1109	0.773	1.10
7000	41.0	56.0	1109	1109	1.31	1.79
8000	64.0	84.0	1109	1109	2.04	2.68
9100	94.7	131.0	1109	1109	3.02	4.18
10000	121.7	21.0	1109	11090	3.88	6.7
12075	23.0	58.7	11090	11090	7.35	18.8
14000	... wire broke—		arc.	...	....	....

Figure of merit of galvanometer 2.88×10^{-9} amp. per mm. defl.

b. The smallest size for which there is no current for wire positive before glow appears is No. 36, diameter 0.136 mm.

c. For sizes larger than No. 36, current and glow appear simultaneously, for wire positive.

d. For wires from about No. 26 up, for the negative polarity, the current and the visible glow appear simultaneously, as a general rule.

Fig. 6 gives curves showing the variation of the glow voltages with the radius of the wire. From these curves the following conclusions can be drawn:

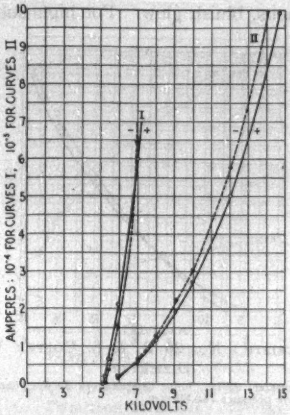


FIG. 4—CHARACTERISTIC: NO. 36 B. & S. COPPER WIRE, 0.135 MM. DIAMETER

Tube 4.45 cm. diameter, 25 cm. long; temperature 25 deg. cent.; relative humidity 45 per cent; barometric pressure 733.85 mm.

e. For the smaller sizes, the negative glow appears before the positive.

f. For the larger sizes the positive glow appears before the negative.

g. The diameter 0.075 mm. is the boundary between these two regions.

Schaffers has noted this crossing of the curves for the starting points of the positive and negative corona and he gives 0.01 cm. radius as the boundary value between the two regions. He does not specify what he considered as the starting point

of the negative corona and therefore it is not practicable to compare his value with that given above.

Variation in the Nature of Corona

During the tests for the characteristic curves a close watch was kept over the appearance of the corona, and there are given below some of the characteristic changes and phenomena which were noted.

For the entire range of diameters there was very little change in the appearance of the positive corona, except for an increase in brightness with the voltage. It always presented a quiet, uniform, continuous, bluish glow. For high voltages the open-

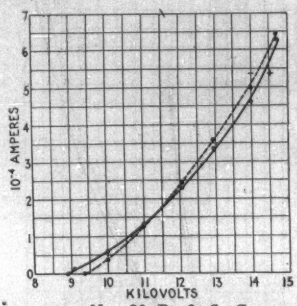


Fig. 5—Characteristic: No. 26 B. & S. Copper Wire, 0.41 mm. Diameter

Tube 4.45 cm. diameter, 25 cm. long; temperature 26 deg. cent.; relative humidity 29.2 per cent; barometric pressure 746.86 mm.

ing and closing of the circuit was attended by a flash of bluish light in the tube and if care was not taken to perform these operations quickly, there was likelihood of an arc starting between the wire and the tube, with the result that the wire, if it was small, was burned in two.

There was considerable change, however, in the appearance of the negative corona with increase of diameter and voltage. The negative corona on small wires starts with a bright spot or two, followed by a mixture of bright spots and brushes as the voltage is increased. With still increasing voltage there is more of a continuous brush-like effect and the discharge becomes quite purple. For the highest voltages the corona is brilliant, purple, continuous, and in constant movement. For

the smallest sizes, the negative corona is likely to take the form of a discharge consisting of isolated, more or less evenly spaced brushes. Marked regularity of spacing has often been observed. The discharge is noiseless for wires up to No. 26 (0.24 mm.), for which diameter a slight hissing appears. As the diameter increases, the hissing grows louder and the diameter of the corona increases.

In the case of the larger size wires, it is the general rule for the continuous negative brush discharge to appear immediately when the critical voltage is reached.

No flash at make or break of the circuit was observed when the wire was negative.

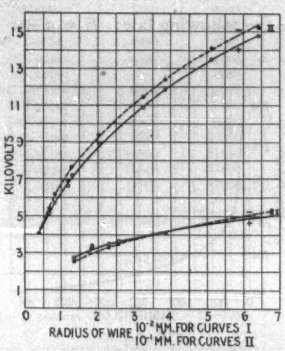


FIG. 6—DIFFERENCE OF POTENTIAL TO CAUSE CONTINUOUS GLOW, AS FUNCTION OF RADIUS OF WIRE

Tube 4.45 cm. diameter, 25 cm. long.

DISCUSSION OF THE CHARACTERISTIC CURVES

A critical comparison of the characteristic curves in Figs. 2 to 5 brings out the following points:

a. For a given voltage, the current increases with decrease of diameter of the wire, also with decreasing pressure.

b. For wires smaller in diameter than No. 40 (0.077 mm.), the current for negative polarity of the wire is always greater than for positive polarity.

c. In the case of No. 40 wire the currents for opposite polarities coincide very accurately for a small rise in voltage above the critical value, and then the negative current becomes and remains the larger.

d. For sizes larger than No. 40, the curves for the two polarities cross. For the lower voltages the positive current is the greater, and *vice versa* for the higher voltages.

e. The characteristic curves become more nearly parallel to the current axis as the diameters increase.

Table III contains the critical and the glow voltage as functions of the radius of the wire, Table IV the glow voltage and the maximum electric intensity at the surface of the wire as function of the radius. While with increasing radius the glow voltage increases, the electric intensity E at the surface of the wire decreases. Fig. 6A shows this relation graphically. As has been found by previous investigators, this electric force E can be represented by the following law: $E = a + \frac{b}{\sqrt{R'}}$. For the

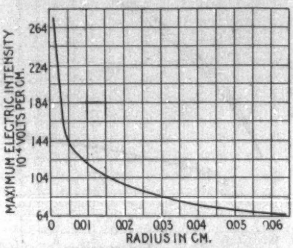


FIG. 6A

smallest wires, there are deviations from this formula, as we should expect, because the critical voltage and the glow voltage differ from each other and as very probably there is a distortion of the field due to ionization before the glow sets in as in the case of two parallel wires. For the positive wire we found $a = 31.6 \times 10^3$; $b = 8.47 \times 10^3$, for the negative wire $a = 35.0 \times 10^3$; $b = 8.06 \times 10^3$.

Influence of Pressure on Coronal Current

The effect of variation of pressure on the voltage to cause continuous glow was studied for a No. 26 wire by varying the pressure in the tube from 768 mm. down to 2 mm., and the results are given in Table V and shown by curves in Fig. 7. Below about 20 mm. pressure it was found impossible to get

a negative uniform glow. Instead of this there appeared a series of beads approximately equally spaced along the wire.

It was found that measurements of the coronal current for

TABLE III

CRITICAL DIFFERENCE OF POTENTIAL TO CAUSE CONTINUOUS GLOW, AS FUNCTION OF RADIUS OF WIRE.

Radius in mm.	Material	Critical voltage	Positive glow	Critical voltage	Negative glow.
0.0135	Silver	2100	2720	1880	2520*
0.0185	Silver	3100	3380	2200	3230*
0.0230	Tungsten	3380	3500	2800	3300
0.0258	Silver		3630		3500
0.0386	No. 40 Copper	3980	4060	3860	4060
0.0678	" 36 Copper	5120	5140	4350	5320
0.0825	" 34 Copper		5710		6140
0.120	Steel " E " String	6600	6600	6760	6840
0.130	" 30 Copper	7180	7180		7660
0.205	" 26 Copper	8900	8900	9370	9370
0.325	" 22 Copper	9700	10880	11440	11440
0.385	" 20 Copper	11850	11850	12075	12400
0.512	" 18 Copper	13500	13500	14040	14120
0.642	" 16 Copper	14700	14700	15220	15220

*These values uncertain on account of dimness of glow.

TABLE IV

R cm.	$V+$volts.	$E+$volts per cm.	$E+$calcul.	$V-$volts.	$E-$volts per cm.	$E-$calcul.
0.00135	2720	2.74×10^5	2.62	2520	2.52×10^5	2.55
0.002185	3380	2.58	2.29	3230	2.45	2.23
0.0023	3500	2.25	2.09	3300	2.08	2.04
0.00258	3630	2.12	1.99	3500	2.02	1.94
0.00386	4060	1.66	1.67	4060	1.66	1.65
0.00678	5140	1.31	1.34	5320	1.36	1.33
0.00825	5710	1.25	1.25	6140	1.21	1.21
0.012	6600	1.07	1.09	6840	1.09	1.09
0.013	7180	1.07	1.06	7660	1.14	1.06
0.0205	8900	0.93	0.91	9370	0.99	0.92
0.0325	10880	0.80	0.79	11440	0.83	0.80
0.0385	11850	0.77	0.75	12400	0.79	0.76
0.0512	13500	0.71	0.69	14120	0.73	0.71
0.0642	14700	0.65	0.65	15220	0.64	0.64

the same wire gave different results on different days and it was considered advisable to find out the influence of pressure for a range around atmospheric pressure in order that the

current readings for the different sizes of wire might be reduced to a 760-mm. basis. Therefore a series of characteristic curves was taken for different pressures with dry air in the tube to do away with any effect which might be due to the moisture in the air. Fig. 8 shows the results obtained. These curves show a marked increase in the current for a relatively small decrease in the pressure. The curves also show an unsymmetrical spacing, which suggests the presence of some disturbing factor.

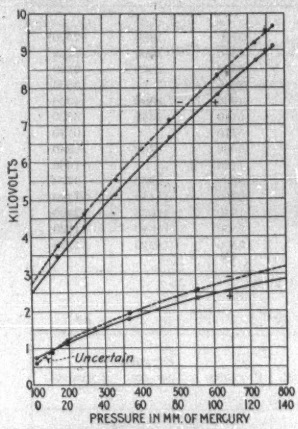


FIG. 7—GLOW VOLTAGE AS FUNCTION OF PRESSURE IN TUBE

No. 26 B. & S. copper wire, diameter 0.41 mm.; tube 4.45 cm. diameter, 25 cm. long; dry air at 25 deg. cent. in tube.

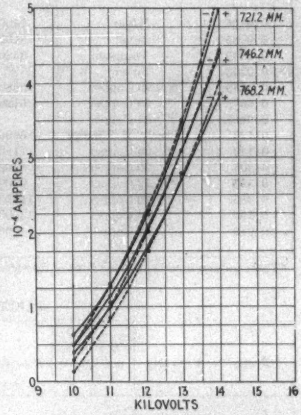


FIG. 8—CHARACTERISTICS FOR VARYING PRESSURE

No. 26 B. & S. copper wire, diameter 0.41 mm.; tube 4.45 cm. diameter, 25 cm. long; dry air at 25 deg. cent. in tube.

In a number of preliminary experiments it was found that it was not possible to repeat observations if the tube was closed and the air not changed. In order to do away with any disturbing effects due to moisture in the air and possible changes in the constitution of the air in the tube, an arrangement was devised for supplying dry air which could be pumped through the tube out into the atmosphere. The air was dried by passing it through two wash-bottles containing concentrated sulphuric acid and then through a tube containing soda-lime. A No. 40 wire was strung in the tube and as the atmospheric pressure

varied from day to day, series of readings were taken as given in Table VII. The general decrease of current with increase of pressure is apparent. The readings for the extreme pressures

TABLE V

VARIATION OF CRITICAL VOLTAGE WITH PRESSURE.

No. 26 B. & S. Copper Wire. Diameter 0.41 mm. Dry Air at 25 deg. cent.

Pressure in mm.	Potential Difference for Continuous Glow	
	+	−
2.0	720	*580
10.9	940	*870
18.9	1110	1200
53.2	1770	1920
91.3	2350	2580
173.5	3450	3750
248.5	425	4610
334.8	5120	5520
483.6	6660	7120
616.6	7800	8330
720.0	8730	9210
746.0	8980	9530
768.3	9100	9640

No continuous glow obtainable—voltage is that of formation of beads.

TABLE VI

p in mm.	$V-$ in volts.	$E-$ in volts per cm. $\times 10^4$	$V-$	$E-$	E average	E calculated
2.	720	0.765	580	0.615	0.69	0.36
10.9	940	0.998	870	0.925	0.96	0.85
18.9	1110	1.18	1200	1.275	1.22	1.14
53.2	1770	1.88	1920	2.04	1.96	2.01
91.3	2350	2.50	2580	2.74	2.62	2.72
173.5	3450	3.60	3750	3.99	3.79	3.97
248.5	4250	4.51	4610	4.90	4.71	4.87
334.8	5120	5.42	5520	5.86	5.63	5.83
483.6	6660	7.08	7120	7.55	7.31	7.36
616.6	7800	8.29	8330	8.85	8.57	8.60
720.0	8730	9.28	9210	9.80	9.54	9.21
746.0	8980	9.51	9530	10.1	9.80	9.70
768.3	9100	9.67	9640	10.2	9.93	9.89

735 mm. and 754 mm. are shown in Fig. 9. These curves show quite a regular variation in the effect of pressure with a tendency toward a greater effect upon the current for negative polarity. This regularity would seem to indicate that the

discordant results obtained in the preliminary experiments were due to the presence of other factors than mere change of the pressure.

To determine what effect, if any, the confining of air in a closed tube had upon the coronal current, a series of tests was run under constant pressure with various conditions as to the closing of the tube, the renewal of the air, etc. The erratic results follow no evident relations and indicate that confinement of the air has a great effect upon the coronal current and also upon the critical and visible glow voltages. Such an effect does not appear strange when one thinks of the quantities of ozone formed and possibly other products, which, when the tube is closed, must remain inside and thus change the character of the gas to a considerable extent. It must be concluded from these tests that it is unsafe to compare results obtained in a closed tube with those obtained where there is a plentiful supply of fresh air.

TABLE VII

EFFECT OF PRESSURE.

No. 40 B. & S. Copper Wire. Diameter 0.077 mm.
in
Tube of diameter 4.45 cm.; length 25.0 cm.
Dry air in tube.
Currents in 10^{-4} amp.

Potential difference	735 mm. +	735 mm. −	738 mm. +	738 mm. −	749.0 +	749.0 −	754.0 +	754.0 −
4000	0.00025	0.00030	0.000076	0.000051	0.000015	0.000015	0.000015	0.000015
5000	0.205	0.176	0.181	0.210	0.150	0.169	0.150	0.169
6000	0.553	0.676	0.557	0.703	0.468	0.611	0.468	0.602
7000	1.06	1.34	1.06	1.35	0.859	1.17	0.900	1.16
8000	1.76	2.28	1.73	2.32	1.38	1.90	1.53	2.02
9000	2.58	3.35	2.53	3.25	2.15	2.86	2.28	2.90
10000	3.45	4.49	3.43	4.52	2.81	3.71	2.99	3.77
12000	6.24	7.64	6.15	8.16	5.17	6.51	5.40	6.83

Positive Corona Appearance.

	735	738	749	754
+				
Jump	4080	4100	4100	4100
Visible	4150	4160	4110	4150

Figures for 738.00 mm. are average of three tests.

Influence of Moisture

In connection with the apparatus for the supply of dry air to the tube, an arrangement was devised whereby air could be drawn from the room through the tube. The humidity of such air was given by calculation from the readings of wet and dry bulb thermometers. Parallel sets of readings were taken from day to day of the current flowing when dry air was pumped continuously through the tube and when air from the room was sucked through before each reading. The readings and the comparative characteristics for 735 mm. pressure and relative humidity 69 per cent are shown in Fig. 10. These curves in-

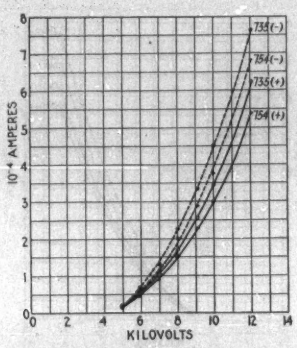


Fig. 9—Characteristic as Influenced by Pressure

No. 40 B. & S. copper wire, 0.077 mm. diameter; tube 4.45 cm. diameter, 25 cm. long; dry air at 25 deg. cent. forced through tube.

dicate a regular effect due to moisture, with a tendency for the decrease of current by humidity to be greater for negative polarity of the wire. The decrease of current by the presence of moisture is well known and these results bear out this effect.

To determine whether the presence of moisture in the air has an effect upon the critical voltage, a test was run as follows, under a pressure of 736 mm. and humidity 68.5 per cent:

Air was sucked through the tube from the room and the voltage was noted at which the initial jump of the galvanometer occurred for wire positive. Then the positive glow voltage was determined and next the negative glow voltage. Then dry air was pumped through the tube and the same measure-

ments were taken. An average of two sets of readings on the uncalibrated low scale of the Kelvin voltmeter gave the results:

	Wet Air	Dry Air
Positive critical voltage.....	4300	4190
Positive glow voltage.....	4350	4260
Negative glow voltage.....	4275	4370

The effect of moisture is then to raise somewhat the starting point of the positive corona and act in the opposite way for the opposite polarity.

With wire negative and moist air in the tube, the discharge begins from dim spots and the discharge is of no clearly defined nature, being a mixture of sections of continuous glow and

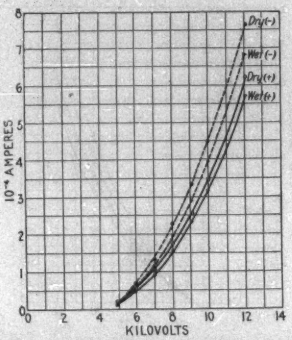


FIG. 10—CHARACTERISTIC AS INFLUENCED BY HUMIDITY

No. 40 B. & S. copper wire, 0.077 mm. diameter; tube 4.45 cm. diameter, 25 cm. long; dry air forced through tube and afterwards air from room drawn through; temperature 25 deg. cent.; humidity 69 per cent; pressure 735 mm.

bright spots, these spots being immobile. The discharge begins quite differently for the same polarity and dry air. As the voltage is increased, suddenly a bright spot will appear. Then for increasing voltage a number of spots appear and they are regularly spaced, increasing in number with the voltage. These brushes are in continual movement back and forth.

The effect of moisture on the appearance of the negative discharge was shown by the following experiment:

The tube was filled with moist air and a voltage somewhat above the critical value was impressed. A mixed discharge resulted as described above. Then a current of dry air was started through the tube and little by little the discharge cleared

up and resolved itself into a line of uniformly spaced brushes which were in continual agitation. If moist air were again admitted, the discharge resumed its former character.

With moist air in the tube and a fairly high potential difference, the wire vibrates circularly for both polarities, describing a torpedo-like figure of revolution. The filling of the tube with dry air diminishes considerably the amplitude of the vibration for wire positive and stops the vibration entirely for wire negative.

Influence of Temperature

The influence of temperature upon the current for a No. 36 wire in a closed tube under a pressure of 760 mm. was deter-

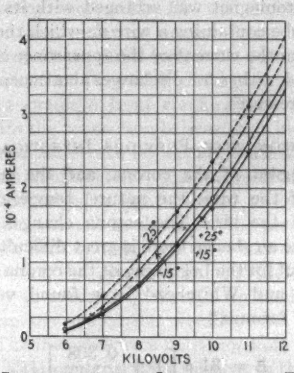


Fig. 11—Characteristic as Influenced by Temperature

No. 36 B. & S. copper wire, diameter 0.135 mm.; tube 4.45 cm. diameter, 25 cm. long; tube closed; dry air in tube under 760 mm. pressure.

mined for the range from 15 deg. to 25 deg. cent. and the results appear in Fig. 11. The lower temperature was obtained by placing cloths wet with alcohol upon the tube and directing a stream of air from a fan upon it. The curves indicate that this difference of temperature makes far more difference in the current for wire negative than for wire positive, both currents showing an increase for increasing temperature, as might be expected.

Material of Wire

An attempt was made to determine the effect of the character of the surface and the material of the wire in the following way. A characteristic curve was obtained for a bright new

steel mandolin " E " string in a tube open to the air. Then the wire was dipped into a solution of copper sulphate long enough to acquire a smooth coating of copper and another characteristic was obtained. Then this wire was amalgamated and another test run. A piece of the same wire was dipped into nitric acid long enough to roughen it without appreciably decreasing its diameter and a test was run on it. Small differences were found to exist in the characteristics, but these differences were accountable for by the changes in humidity and pressure during the time of running the series of tests. It was noticed that originally polished copper wires became rough on the surface through the action of the corona.

A strong electromagnet was arranged with its poles in close proximity to a tube containing a wire on which there was corona and no effect upon the current or the appearance of the discharge could be detected, either for discharges at atmospheric pressure or at reduced pressures.

Comparison with Previous Investigations

The starting point of the corona, and the current, depend on the radius of the wire, the nature, temperature, pressure and humidity of the air. The corona changes the chemical constitution of the air, hence there is great difficulty in formulating the laws. But for the beginning of the corona and relatively large radii Peek and Whitehead have found very neat laws expressed by the formula*

$$E = 31\,\delta\left[1 + \frac{0.308}{\sqrt{\delta R}}\right]$$

$$\delta = \frac{3.92\,p}{273 + t}$$

E is the critical electrical intensity at the surface of the wire, R the radius in cm., p the pressure in cm. of Hg. and t the temperature in degrees centigrade. In Table VI the critical electrical intensity has been calculated by means of this formula and the agreement between the calculated and the average electrical intensity or the negative value is quite satisfactory as far down as 5.32 cm. of mercury, while below this pressure discrepancies are noticeable.

*J. B. Whitehead. *The Electric Strength of Air.* Trans. of A. I. E. E. Vol. XXXII, 1913, p. 1317.

According to Whitehead the electrical intensity E is independent of moisture content, and the current of the corona decreases by the presence of moisture. This latter statement agrees with our observations, but for the fine wires used in this investigation moisture also affects the starting point of the corona.

Pressure Due to Ionization

During the first set of experiments to determine the influence of the pressure upon the coronal current for pressures around atmospheric it was noticed that when the potential difference was applied the manometer connected to give the pressure inside of the tube showed a sudden increase of pressure. This sudden increase was most noticeable for the highest pressure and amounted to a centimeter or more. Since it was desired to keep the pressure in the tube constant a carboy was connected to the tube to act as a reservoir of large capacity and prevent the increase of pressure from reaching any noticeable value.

To investigate the connection between this increase of pressure and the potential difference impressed, a sensitive U-tube open manometer was constructed. The manometer had a bore of 2.8 mm. and contained a light mineral oil of specific gravity 0.859. It was connected to the tube, the pressure in the tube was adjusted to atmospheric, the tube was sealed up and the sudden increase of the pressure was noted for voltages from those necessary to produce the corona up to those causing the maximum jump the manometer would permit without forcing the oil out. The increases were noted for both polarities of the wire. Table VIII contains data relative to the size of the wire and tube, the readings observed and the increases of pressures reduced to terms of millimeters of mercury. Fig. 12 shows the increase of pressure plotted against potential difference.

For the positive polarity of the wire, there was no appreciable increase of the pressure until the corona appeared. When the wire was negative, the presence of a small brush or two caused the level of the columns to differ appreciably before the general discharge appeared along the wire.

The jump for wire negative was greater than for wire positive for the greater part of the range of voltage and it will be seen that the general shape of the curves is the same as that of the characteristic curves for the same size of wire as given in Fig. 11. Furthermore, by comparing the numerical values of the currents and increases of pressure for like voltages it will be found that

TABLE VIII.

PRESSURE DUE TO IONIZATION

No. 36 B. & S. wire. Tube 4.45 cm. internal diameter, 25 cm. long, volume 388 cu. cm. Dry air in tube, pressure 744.0 mm., temp. 26 deg. cent.
Manometer bore 2.8 mm., containing mineral oil of 0.859 specific gravity.

Wire Positive					Wire Negative				
Potential difference	Manometer—cm. Left	Right	Diff.	mm. of mercury	Potential difference	Manometer—cm. Left	Right	Diff.	mm. of mercury
5340	Jump barely visible.			0.000	4800	Jump barely visible			0.00
6180	12.22	13.30	1.08	0.682	6180	12.20	13.25	1.05	0.664
6680	12.19	13.59	1.40	0.885	6700	11.98	13.50	1.52	0.96
7080	11.72	13.82	2.10	1.33	7100	11.70	13.75	2.05	1.30
7440	11.48	14.10	2.62	1.66	7500	11.40	14.08	2.68	1.70
7820	11.00	14.56	3.56	2.25	7850	11.05	14.40	3.35	2.12
8200	10.80	14.79	3.99	2.52	8220	10.70	14.80	4.10	2.59
8620	10.36	15.20	4.84	3.06	8600	10.40	15.10	4.70	2.97
9200	9.75	15.80	6.05	3.83	8860	9.92	15.60	5.68	3.59
9800	9.0	16.5	7.5	4.74	9400	9.3	16.2	6.9	4.36
10400	8.3	17.3	9.0	5.69	10500	7.6	17.8	10.2	6.45
10840	7.4	18.1	10.7	6.76	11000	6.8	18.5	11.7	7.39
11300	6.6	18.8	12.2	7.71	11460	5.9	19.4	13.5	8.53
12200	4.8	20.3	15.5	9.80	11940	4.5	20.7	16.2	10.2
12900	3.3	22.1	18.8	11.9	12640	2.5	22.3	19.8	12.5
13840	1.1	24.3	23.2	14.7	13520	0.4	24.2	23.8	15.0
14200	0.2	25.2	25.0	15.5					

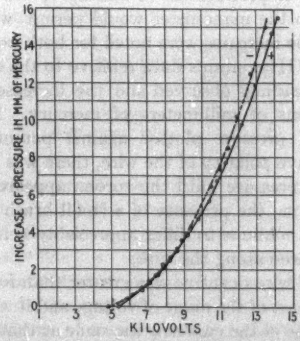


FIG. 12—INCREASE OF PRESSURE DUE TO IONIZATION

No. 36 B. & S. copper wire, diameter 0.135 mm.; tube 4.45 cm. diameter, 25 cm. long. Curves show sudden increase of pressure in closed tube when potential difference is applied. Dry air, pressure 744 mm.

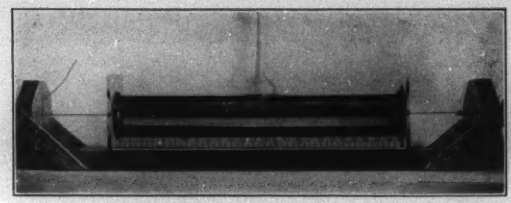
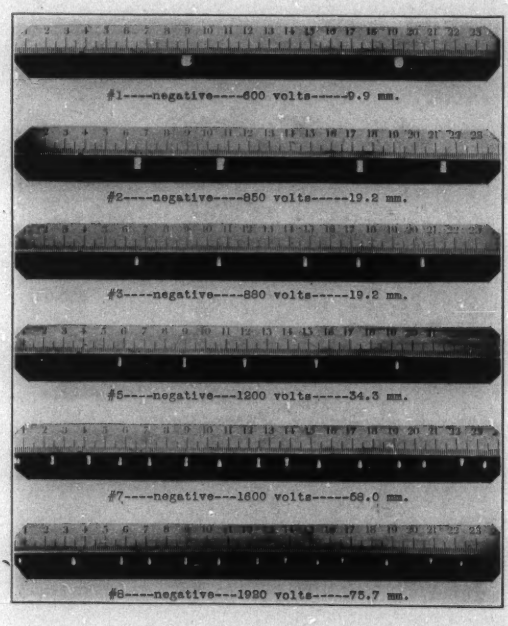


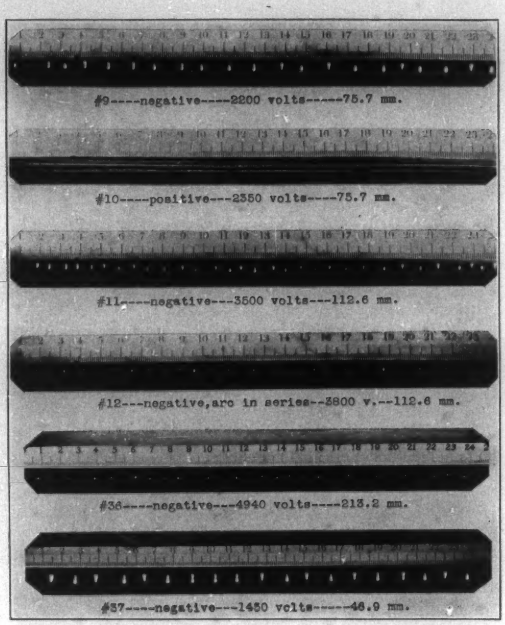
FIG. 13—TUBE USED FOR PHOTOGRAPHS [FARWELL]

B. & S. wire, diameter 0.26 mm.; tube 3.5 cm. diameter, 25 cm. long; with longitudinal slit 0.6 cm. wide.



Series No. 1—Pressure in tube and potential difference varied. [FARWELL]

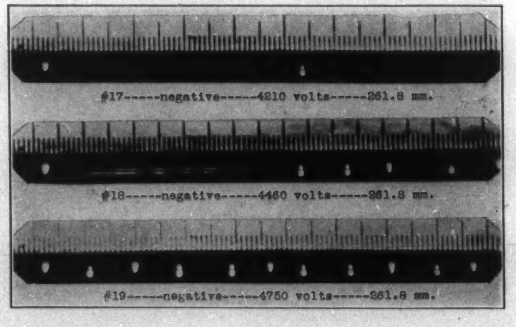
FIG. 14—CHANGES IN NATURE OF ISOLATED BRUSH DISCHARGE WITH POTENTIAL DIFFERENCE AND PRESSURE



[FARWELL]

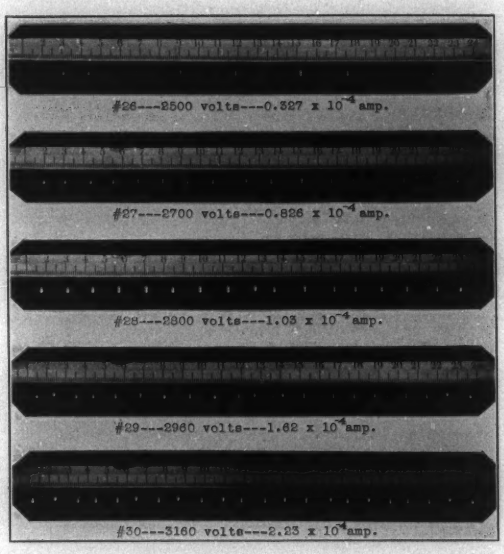
Series No. 1 (continued)—Pressure in tube and potential difference varied.

FIG. 15—VARIOUS FORMS OF DISCHARGE AT REDUCED PRESSURES



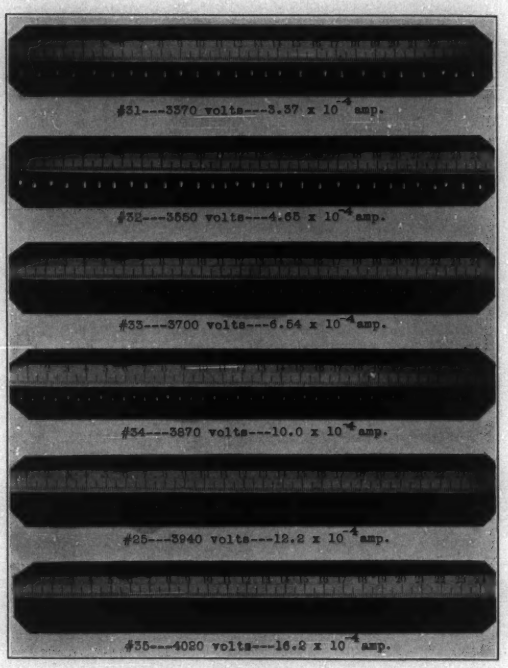
Series No. 3—Wire negative—pressure constant. [FARWELL]

FIG. 16—EVOLUTION OF NEGATIVE ISOLATED BRUSH DISCHARGE FROM CONTINUOUS GLOW



Series No. 5—Wire negative—pressure constant. [FARWELL]

FIG. 17—VARIATION OF NUMBER OF BRUSHES WITH POTENTIAL DIFFERENCE—GLOW VOLTAGE 2440



[FARWELL]

Series No. 5 (continued)—Wire negative—pressure constant at 119.6 mm.

FIG. 18—VARIATION OF NUMBER OF BRUSHES WITH POTENTIAL DIFFERENCE

they are proportional. This shows that the increase is an ionization phenomenon, for if the sudden increase were due to the heating effect of the current we would expect the increases to vary as the square of the currents instead of the first power.

The theory of ionization would lead one to expect such a jump when the gas is suddenly ionized; some particles in the gas would be split up by collisions and each of the constituent parts would act as a separate molecule as far as its contribution to the total pressure is concerned.

This ionization pressure might serve as a principle upon which to build a high-tension voltmeter, for if such a tube were once calibrated, the indications of the manometer would give a measure of the potential difference impressed.

Discontinuous Brush Discharge

As already mentioned, at low pressure and negative polarity of the wire, the discharge took the form of isolated beads or brushes disposed with approximate regularity along the wire. In order to be able to see the wire broadside a glass tube was lined with a piece of sheet brass of such a width that a longitudinal slit was left along the tube, thus permitting inspection of the discharge along the central wire. The glass tube was closed at the ends by glass plates with central holes drilled through them. The wire passed through these holes and could be tightly stretched by means of a thumbscrew. The dimensions of the apparatus are given in the illustration, Fig. 13. This picture shows the branch tube through which the air could be exhausted and a wire along this tube connecting with the brass sheath. The holes around the wires where they passed through the glass plates were stopped by means of soft wax, the tube was exhausted and then filled with dry air by admitting air from the room through the drying apparatus mentioned previously. Then various forms of discharge were produced and photographs taken of them.

Series 1, Figs. 14 and 15, was taken to give an idea of the development of the discontinuous discharge from a few intensely bright beads to a series of small brushes spaced with considerable regularity along the wire. For the lowest pressures the beads consist of a bright cylindrical core along the wire, which core is surrounded by a narrow dark space, enveloped in turn by a purple glow of relatively large diameter. For increasing pressure the central core contracts to a point and the discharge, instead of surrounding the wire to form a bead, starts from this bright

point and spreads out fan-like in a plane at right angles to the wire. For still higher pressures the fan seems to shut up and finally degenerates to a small brush. For all of the illustrations in Series 1, except No. 36 and No. 37, the wire was not stretched tightly and therefore the regularity of spacing of the brushes is not very great. The two photographs from which these illustrations were made were taken with the wire tightly stretched, and the regularity of spacing is apparent. No. 10 shows the typical uniform positive glow. No. 12 shows the effect upon the brush discharge of inserting an arc in series with the tube.

Series 3, Fig. 16, shows the evolution of the isolated brush form

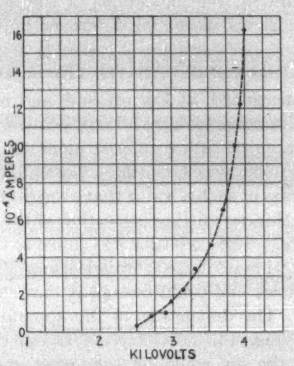


FIG. 19—NEGATIVE CHARACTERISTIC

No. 30 B. & S. copper wire, 0.26 mm. diameter; slit tube 3.5 cm. diameter, 25 cm. long; pressure in tube 119.3 mm.

of negative discharge from a continuous glow. For a potential difference just above the critical value, the negative wire was enveloped by a more or less hazy continuous discharge. Keeping the pressure in the tube constant and raising the voltage slightly causes some of the glow to turn into brushes, and with increasing voltage all of the glow is converted into the uniformly spaced form of brush discharge. Sometimes conditions can be arranged so that the brushes appear one after another with apparently no change in the conditions.

Series 5, Figs. 17 and 18, was taken to find, if possible, some definite relation between the number of brushes and the potential difference for a given pressure in the tube. The increase of

the number of brushes with the voltage and the regularity of spacing of the brushes is apparent. Photographs were taken at voltages where the distribution of brushes was most regular. For the highest voltages, the brushes were in constant movement back and forth along a short path, and to secure a good picture it was necessary to make the time of exposure quite short.

Fig. 19 is the characteristic curve for the currents and voltages employed in Series 5. This graph shows the rate of increase of current with voltage to be very great at the highest voltages employed.

Fig. 20 shows the number of brushes as a function of the potential difference. In some of the photographs some of the brushes were seen to be smaller than the rest and for the plotting

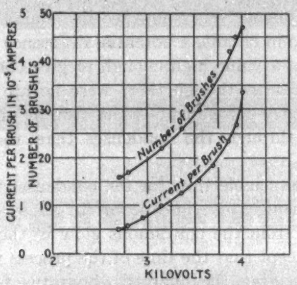


FIG. 20—NUMBER OF BRUSHES AND CURRENT PER BRUSH AS FUNCTION OF POTENTIAL DIFFERENCE

No. 30 B. & S. wire in slit tube; pressure 119.3 mm.; wire negative.

of the graph the estimated equivalent number of full-sized brushes was taken. Evidently the number of brushes is some well-defined function of the potential difference. Between the voltages at which the arrangement of brushes was most regular, there seemed to be a transition period in which there were many little brushes in addition to the larger ones. An increase of voltage would then produce a set of full-sized brushes.

The lower curve of Fig. 20 gives the variation of the current per brush on the assumption that the total current is carried by the brushes.

EFFECT OF SHORT ARC UPON DISCHARGES

Nature of the Phenomenon. Series No. 2, Fig. 21, shows the effect of a short arc in series with the tube upon the character of

the positive and negative discharges for a constant pressure in the tube and an approximately constant difference of potential.

The typical quiet bluish positive discharge shown in No. 13 is changed to No. 14, which is more brilliant, of a purple tinge and greater in diameter. In addition its boundaries seem more ragged.

The typical discontinuous negative discharge has its character changed most markedly by the introduction of the arc. No. 16 shows the changed discharge; it seems to be made up of two effects superimposed upon each other. The arc evidently sets up high-frequency oscillations in the circuit and an alternating effect is superimposed on the direct-current phenomenon. To test whether this theory was correct, the following experiment was tried:

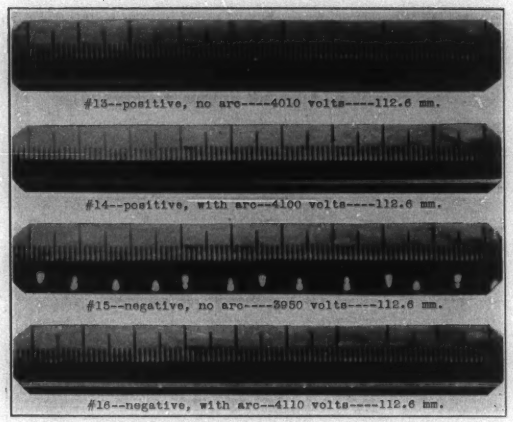
A two-mf. condenser was connected in parallel with the tube, and with the arc in circuit, a potential difference was impressed upon the tube of a value high enough to give corona. The appearance was then as though there were no arc in the circuit. The high-frequency component of the current prefers rather to take the path through the condenser than to go across the air gap.

It took an appreciable time for the condenser to become fully charged and during this time occurred the evolution of the brush discharge from the continuous glow in the manner mentioned above, except that the time of the process was prolonged.

Upon disconnecting the charged apparatus from the source of potential, the discharge through the tube persisted for some seconds, due to the discharge of the condenser through it. As the voltage of the condenser fell, the number of the brushes became less and their brightness diminished until they vanished. During this discharge, the brushes maintained quite a regular arrangement.

By assuming fair values for the electrical constants of this discharge circuit, it is easy to calculate that the discharge of the condenser must be of the continuous type. This being the case, it is evident that the negative discontinuous discharge must be essentially a direct-current phenomenon.

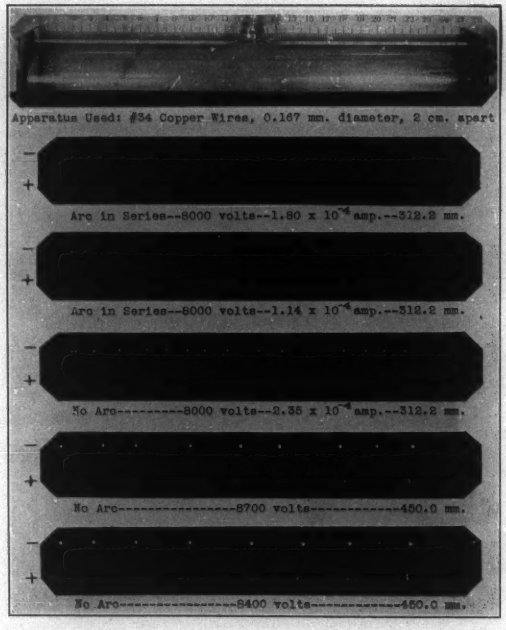
It should be remarked that the values of current given for the cases where an arc is in circuit represent only the continuous components, since the galvanometer deflection is unaffected by the alternating components. There is hardly another phenomenon which shows so directly the difference between positive and negative electricity as the foregoing illustrations.



Series No. 2. [FARWELL]

FIG. 21—EFFECT OF SHORT ARC IN SERIES ON NATURE OF DISCHARGES

No. 30 B. & S. wire in slit tube; pressure constant at 112.6 mm.



Series No. 6. [FARWELL]

FIG. 22—TWO PARALLEL WIRES—REDUCED PRESSURE

Nevertheless the question may be raised as to whether the isolated brush form of discharge may not be due to oscillations in the circuit. In order to make it clear that this is essentially a direct-current phenomenon, there follow some experiments and arguments which support this view.

The appearance of the brushes and the current indicated by the galvanometer are constant for a given voltage, no matter what combination of machines is used as the source of potential. One of the sets may be used and the appearance of the spots and the voltage and current noted. Then if the other set be used to give the same voltage with a different number and speed of machines, the same results are obtained. If there were oscillations set up perhaps by sparking at the brushes, we would not expect this agreement.

Mention has been made before of the effect of the introduction of a condenser in parallel with the tube. To test whether the current sent through the tube by the condenser in discharging was direct or oscillatory, another experiment was performed. The condenser was connected across the positive and negative busbars to which the generating apparatus was connected through the water resistance. Then a switch connecting the machines to the busbars was closed, as was also a switch leading to the tube. The deflection of the galvanometer was noted and the appearance of the brushes. Then the generator switch was opened and the condenser discharged through the tube and the galvanometer. After the switch was opened, the galvanometer deflection gradually decreased, the rate of the decrease being slower and slower as the discharge proceeded. The opening of the switch caused no immediate change in the brushes, only the gradual change already noted. That the discharge of the condenser must be continuous is shown by the deflection of the galvanometer and it can be further proved by a rough calculation. Assuming the resistance of the cylindrical field as given by E/I and taking a set of values of E and I for the comparatively low pressures at which the brushes are best formed, we obtain $R = 1.83 \times 10^6$ ohms. Assuming the very large value of 0.1 henry for the inductance of the circuit, and the approximate value of 2 mf. for the capacity, we find that R is about 4.1×10^4 times as great as $\sqrt{4L/C}$ and hence it is clear that the condenser discharge must be of the continuous type.

By running wires from the terminals of an induction coil

to the central wire and the tube and then adjusting the discharge points on the coil to such a distance that a silent discharge took place between them, it was possible to obtain an almost uniform hazy glow along the wire. But no effect could be obtained like the uniformly spaced brush discharge.

It is well known that an arc is the source of electrical oscillations and it has been shown by a previous figure that a short arc in series with the tube disturbs the brushes due to the direct current by the superposition of an alternating-current effect, so that the glow becomes more or less uniform and the difference in the appearance of the glow for different polarities becomes much less. So the introduction of an oscillatory current acts to suppress the isolated brush form of discharge and not to cause it.

It should be stated here that Peek* by a stroboscopic method has also observed "more or less evenly spaced beads" on the negative wire when there was corona between parallel wires caused by an alternating difference of potential of 80,000 volts at atmospheric pressure. The wires used by Peek were 0.168 cm. in diameter, spaced 12.7 cm. apart.

Corona between Parallel Wires

Phenomena at Reduced Pressures. Two No. 34 wires, 0.167 mm. in diameter, were arranged parallel and two centimeters apart inside of a glass tube as shown in Fig. 22 and photographs were taken of the discharge between them at reduced pressures. The three lower illustrations of Fig. 22 show the typical isolated brush discharge on the negative wire with corresponding luminous section of the positive wire. The negative brushes had a brilliant nucleus with a fainter glow spreading out from it. For lower pressures than those for which the photographs were taken, the discharge became more brilliant; the brushes spread farther apart and increased in size. Each section of positive glow was usually of uniform brilliance. But for comparatively low pressures and high voltage, these positive sections became somewhat discontinuous, bright spots being mixed in with the uniform glow.

The introduction of a short arc in series made a marked change in the nature of the discharge. Both wires were more or less completely covered with a nearly uniform glow and there was no longer any marked difference between positive

*Trans. A. I. E. E., 1912, Vol. XXXI, p. 1089, and Plate LVII.

and negative. The brilliancy of the discharge depended upon the fatness of the spark. With the arc in series, low pressures and a relatively high voltage, the discharge between the wires resembled a sheet of luminous rain. An intermediate effect showed bluish streamers between the wires.

It should be remarked that the values of current given for the cases where an arc was used are only the continuous components of the current.

Phenomena at Atmospheric Pressures. Two No. 36 wires were stretched over hard rubber bridges so as to be parallel and three centimeters apart and a characteristic test was obtained for the discharge between them. The dimensions of the wires,

TABLE IX.

Two Parallel No. 36 Wires—0.135 mm. diam., 36.2 cm. long and 3.0 cm. apart.

Temperature 26.5
Relative Humidity 43.0 per cent
Barometric Pressure 749.0

Potential Difference	Deflection in mm.	Shunt Factor	Current in 10^{-4} amp.
6000	0.3	1.0	0.000015
6400	0.5	1.0	0.000025
6500	Critical Voltage		
7000	125.0	1.0	0.00634
8000	37.0	12.832	0.0241
9000	75.0	12.832	0.0488
10000	30.0	128.32	0.195Glow sets in
12000	198.0	128.32	1.29
14000	49.0	1283.2	3.19

$F = 5.07 \times 10^{-9}$ amp. per mm. deflection.

the atmospheric conditions and the data for a characteristic curve are given in Table IX. A sudden increase of the deflection of the galvanometer marked the critical voltage as in the case of former tests with wires in a cylindrical field. It was noted in this test that there was a considerable current flow between the wires before there was any indication of a glow. At 10,000 volts a flickering glow along the positive wire gave the first indication of a general glow.

When the visible discharge was fairly started, it took the form of a uniform continuous glow along the positive wire and a fairly regular arrangement of brushes along the negative wire. This discharge was examined on a day when the humidity was considerably greater and it was noticed the negative discharge had

lost all appearance of a regular distribution and there was more of a continuous glow effect.

It was noticed that the negative wire bowed in toward the positive and that the positive bowed away from the negative. This effect was noticed in one of the preliminary experiments with an influence machine.

When the wires were purposely made rather slack in order to intensify the effect it was found that the positive wire vibrated strongly with a circular motion and that the negative was motionless. If the polarity of the wires was reversed, the phenomenon reversed also and it was still the positive wire which vibrated.

Exploration of Field between Parallel Wires. A glass tube with a platinum contact wire projecting axially from its tip was fixed into a wood block in such a manner that when the block was moved across a board beneath and parallel to the plane of the wires, the platinum contact point moved in the plane of the wires. By means of a scale fixed across the board perpendicular to the direction of the wires, it was possible to set the contact point at any desired position between the wires. When the ground terminal of one of the electrostatic voltmeters was connected to the grounded negative wire and the high-tension terminal was connected to the contact point it was found that the voltmeter deflected when there was a current flow between the wires and the contact point was in the neighborhood of the wires. So long as there was no current flow between the wires there was no deflection.

Figs. 23 and 24 show the curves for field distribution as plotted from the data, and also the distribution of the electrostatic field between the wires as calculated from the formula for the electrostatic field on a line between the axes of parallel wires. If P denotes the point where the potential is desired, A and B the inverse points of the circular sections of the wires and q represents the charge per unit length of one wire, the potential V at the point is given by

$$V = -2q \log (AP/BP)$$

Sufficient accuracy was obtained for the purpose in hand by taking the inverse points as at the centers of the wires.

An examination of the curves for the actual distribution of the field discloses the fact that there are large anode and cathode falls of potential, the anode fall of potential being the greater for the two lower potential differences. For these also the

actual field departs widely from the electrostatic. For the 12,000-volt curves the actual and electrostatic fields become more alike.

The field is distorted through ionization, because the positive ions are driven toward the negative wire and form a layer of positive electricity round about the negative wire. Hence there results a very large fall of potential around this wire. Around the positive wire there is an accumulation of negative electricity and hence there is a fall of potential here also. But the positive and negative ions are of different size and mobility, and therefore the distortion of the field about the positive wire is different from that around the negative wire.

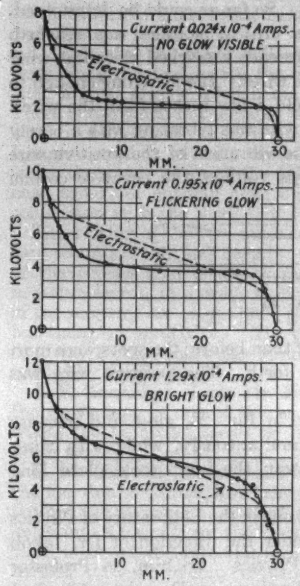


FIG. 23—DISTRIBUTION OF THE POTENTIAL BETWEEN TWO PARALLEL WIRES 0.135 MM. IN DIAMETER, 30 MM. APART

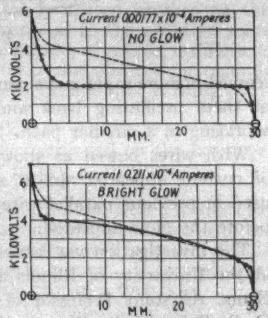


FIG. 24—DISTRIBUTION OF THE POTENTIAL BETWEEN TWO PARALLEL WIRES 0.052 MM. IN DIAMETER, 30 MM. APART

Notes on Test. At voltages a little above the critical voltage there is a noticeable lag of corona behind e.m.f.; in the extreme case this lag amounted to a second or so. Spots on the negative wire appear first, then the general glow, which appeared to move along the positive wire from the end leading to machines,

The negative glow is by far the brightest and is inclined toward a purple, while the positive glow is blue. With the high humidity, there was no regularity in spacing of brushes, and much continuous glow on the negative.

An attempt was made to see whether after corona was formed and then the potential difference was lowered, below the critical value, the corona would persist. So far as could be determined, the corona stopped when the critical voltage was reached.

At 13,000 volts potential difference a marked electrical wind was noticed proceeding from the wires. It was strong enough to be noticed on the face when held a few inches from the wires.

At this voltage, the negative wire was vibrating with a barely perceptible movement, while the vibration of the positive wire was excessive. And also at this voltage, the negative corona

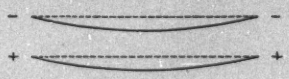


FIG. 25

seemed in more rapid movement than before; the spots were most of them oscillating back and forth. The positive wire was vibrating in a circular path.

With wires bowed as shown in Fig. 25, glow and increase of current appeared almost simultaneously, while with wires used in previous parallel wire test, the jump took place long before the glow appeared.

This investigation was carried out in the Laboratory of Physics at the University of Illinois under the direction of Dr. Jakob Kunz, Assistant Professor of Physics. To him, to Professor E. B. Paine of the Electrical Engineering Department and to Professor A. P. Carman of the Department of Physics, the author wishes to acknowledge his indebtedness for many helpful suggestions as to the conduct of this work.

Discussion on "The Corona Produced by Continuous Potentials" (Farwell), New York, November 13, 1914.

L. W. Chubb: The author makes certain apologies about the paper, saying it is more of technical interest than commercial value, compared with the alternating-current corona. That may be so, but I believe there is a good deal of commercial value in the study of the direct potential in connection with electrical precipitation, and our fundamental study of the electron theory and effects of ionization.

I think also the paper will stimulate a good deal of further work along this line, just as the first few papers on corona stimulated a great number of papers in the alternating-current work. There is too much in the paper to grasp or remember from reading it over once, but I think it is a very good paper for our records. I cannot read it without thinking of the various explanations which there may be for all the different phenomena he finds, some new, some not entirely new, but they have a very important connection with the work that is going on.

The bowing of the two wires in the same direction is a significant condition that has been brought out; and the concentration of the corona into beads or regularly spaced brushes on the negative seems, in a way, to correspond to the negative spots in the mercury arc or gas arc—the nature, of course, is different, but there is a similarity. The glow on the positive corresponds in a way to the luminosity around an anode that is being bombarded by the electron.

A. E. Kennelly: I ask Mr. Peek if he can throw any light on the movement of one of the wires, mentioned on the last page, where the vibration seems to be rotary as distinguished from being simply to and fro.

P. M. Lincoln: Some years ago Mr. Peek gave a formula for the loss due to corona, and that formula contained, as one of the factors, the frequency. I asked at the time why frequency should enter into a formula for the loss due to corona. It seemed to me that if it entered into this formula properly, then if we carried it down to zero frequency we would have zero loss. This paper this evening does not seem to indicate we have zero loss at zero frequency. What is the proper relation between frequency and loss? Perhaps Mr. Peek can answer that.

Max von Recklinghausen: One of the phenomena mentioned in the paper of Mr. Farwell, reminds me of a phenomenon which appears in the mercury vapor arc, which has hardly been described, namely, the appearance of luminous beads on the positive electrode. They are easiest to distinguish in the lamp shown in the sketch. We have four distinct luminosity phenomena in such a lamp, namely, (1) the disintegrating point, at the negative pole, (2) the pink negative flame, (3) the luminous column, the

most typical light phenomenon in the mercury vapor lamp, and finally (4) the pink bead phenomenon near the positive. This latter can only be seen under certain conditions of temperature and vacuum, but just this phenomenon resembles vaguely the one described by Mr. Farwell. The number of beads will change rapidly with change of conditions.

I want to say one thing regarding the corona loss. I would like it to be quite clear in our minds that economically this plays a very small part in a direct-current power transmission line. I mention this because I think it of importance that the smallest possible impediment should be thrown in the way of the development of high-tension direct-current power transmission.

L. T. Robinson: When the papers on alternating-current corona were discussed June 27, 1913, (TRANS. A. I. E. E., Vol. XXXII, p. 1810,) the fact was brought out at the meeting that the glow started a long time before the discharge started, and that we had there a rather satisfactory means, apparently, for the measurement of the high potential. But here it appears that it is even better, that is, that this critical voltage appears to be a very sharp point, and we have the commencement of the large flow on the galvanometer a long time before the glow sets in. I simply call attention to the fact that there is a definite and sharply defined effect there which I think could be put to some useful purpose.

Selby Haar: I think it will be of great interest if Mr. Farwell will give a detailed description of the generators which he uses for producing this high voltage, and also state whether they were designed under his supervision or by commercial manufacturers, and furthermore tell us why the particular sizes which were selected were chosen.

F. W. Peek, Jr.: In selecting a conductor in transmission work it is of particular importance, from the corona standpoint, to be able to predict the voltage at which loss starts. In general the operating voltage should be at or below the fair weather *disruptive critical voltage*. This paper tonight shows, as other papers have shown, that the starting voltage depends upon the maximum of the voltage wave. If the single-phase alternating critical voltage is 100 kv. effective for a sine wave, the continuous critical voltage is 141 kv. for the same conductor arrangement. The formula for the single-phase alternating effective voltage can thus be used for direct current; it is simply necessary to multiply by $\sqrt{2}$. Watson's investigations also show this. It means that in practise about 40 per cent higher continuous voltages may be used than with single-phase alternating current. Compared to three-phase alternating current, the difference is greater. (It is simply necessary to consider voltages to neutral.) This point in its favor, however, will not cause direct current to supersede alternating current in high-voltage transmission.

This one advantage for direct current is still greater in solid dielectrics, as cables. In air and oil there is very little loss

until a certain definite voltage is reached. In solid dielectrics, loss starts as soon as voltage is applied and increases approximately as the square of the applied voltage—the consequent heating reduces the strength of the insulation. There is thus a gain here for direct current. It is questionable, however, how far this may be made use of, as cables generally break down by abnormal or transient voltages, which take place in either alternating-current or direct-current circuits. One other advantage is the elimination of the large capacity current.

In my 1912* paper, I gave the results of a stroboscopic study of alternating-current corona; that is, the corona was viewed through an instrument in which one could see the corona due to the positive half of the wave or due to the negative half of the wave. Photographic records were shown. It is very interesting to note that the positive corona, as shown by direct-current tests, is the same as the corona due to the positive half of the alternating-current wave; and vice versa, the same effects are observed for the corona on the negative half of the wave. If that paper is referred to, it will be seen that when the wires are very smooth and the negative half of the wave is observed, the negative corona first appears as a reddish crown around the wires. Finally, after operating a short time, the corona separates into more or less evenly spaced beads along the wires. In some cases, instead of taking the bead form it takes a spiral form. The positive corona is a bluish color and fits the wire surface very closely. With points, just the opposite effect occurs. The positive corona extends away out into a brush, whereas at the negative, there appears a red hot point. This difference is evidently due to the greater stress or higher gradient at the point, where new sources of ionization occur, perhaps from the metal itself.

Mr. Farwell shows that, except for very small wires—wires smaller than one-tenth of a millimeter—the alternating-current formulas may be applied for starting voltage, temperature, pressure, etc.

Dr. Kennelly has noted the photograph of the wire rotating due to corona. The same effect is also obtained with alternating current. In fact, by referring to my 1912 paper, it will be seen that in one case the wire is made to rotate as a whole, while in another, a node is formed in the center. For this particular case it is also a frequency meter. It shows on one half of the rotation negative corona and on the other half positive corona. It is thus rotating at the frequency of the applied voltage.

A. E. Kennelly: Does the spiraling action you mention account for it?

F. W. Peek, Jr.: I do not know. I first observed the vibration of wires due to corona several years prior to the 1912 paper. Two steel wires, each 500 feet long, were stretched between two transmission towers. The spacing was perhaps ten feet. These wires vibrated; one as a whole, and the other in three

*Trans. A. I. E. E., Vol. XXXI, 1912, p. 1051.

parts or with two nodes. The period was very slow, about sixty a minute. That vibration seemed to be back and forth, perhaps on account of the long span. It started when voltage in the neighborhood of 200 kv. was applied. The vibration was imperceptible when the voltage was first applied, but the amplitude gradually increased until it seemed the wires would soon come together.

Mr. Lincoln asks why, if there is a loss on direct current, the formula for the alternating-current loss indicates zero loss at zero frequency, thus

$$p = a\,f\,(e - e_0)^2 \qquad (1)$$

There is a loss in direct current. For the same maximum voltage the direct-current loss is perhaps in the order of one-fourth the corresponding loss at 60 cycles, but for the same effective voltages the direct-current loss is very much less. Zero frequency and direct current are not necessarily identical.

The greater part of the alternating-current loss is a "per cycle" loss. There is, however, a small constant loss. The more complete equation is

$$p = a_1\,(f + k)\,(e - e_0)^2 \qquad (2)$$

Where the frequency does not vary greatly from 60 cycles, (1) is more convenient to use in practical work; (2) is used over greater range. This equation was published more completely in my paper read before the Franklin Institute* about a year ago, and it was also given in my discussion† at the A.I.E.E. Cooperstown convention. The complete formula can be found in the *Journal* of the Franklin Institute.

I will speak briefly of another sort of corona. High-frequency corona, low-frequency corona, and direct-current corona have been discussed and are covered by the formula for alternating-current corona. There is another sort of corona—the corona transients, of single impulses. It takes energy and, therefore, a very small but definite time to start a spark or corona. For continuously applied alternating or direct-current voltages the time is, relatively, practically unlimited. When the time is limited, however, as in a transient of steep wave front, or a single impulse of short duration, much higher voltages are required to produce the same effects, or to spark the same distance, than when the time is not limited. This applies not only to air, but also to oil and solid insulations. I have made such a study and find, for instance, for a given shape of impulse reaching its maximum in $\frac{1}{4{,}000{,}000}$ second, a certain needle gap

* "High-Voltage Engineering," Franklin Institute *Journal*, Dec. 1913.

† TRANS. A. I. E. E., 1913, Vol. XXXII, Part II, 1819.

in air requires approximately double the 60-cycle voltage to spark over. For the same impulse reaching its maximum in $\frac{1}{400,000}$ second, the spark voltage is 25 per cent higher than the 60-cycle voltage. The time lag has in this way been accurately measured. For continuously applied alternating or direct-current voltages the initial ionization, within reasonable limits, has no effect on the corona starting voltage. For single impulses the effect may sometimes be appreciable.

S. P. Farwell: The generators used were at hand in the E. E. Department of the University of Illinois. They had been constructed without my supervision by the manufacturing company. I acknowledged in the paper the fact that F. W. Peek was the first to record beads along the negative wire in the alternating-current corona. As has been mentioned, the investigation has opened a number of new questions and further experimental and theoretical researches are in progress in the University of Illinois. The theories so far advanced cannot account for the large variety of phenomena in the corona.

Presented at the 301st Meeting of the American Institute of Electrical Engineers, New York, November 13, 1914.

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GRAPHIC METHOD FOR SPEED-TIME AND DISTANCE-TIME CURVES

BY E. C. WOODRUFF

ABSTRACT OF PAPER

The paper presents a very simple method for obtaining speed-time and distance-time curves, which avoids the usual step-by-step process with its tedious calculations. The method consists of plotting certain so-called "service characteristics" upon the diagram of motor characteristics with the speed-current and traction-current curves. The time and distance increments corresponding to assumed speed increments are found by simple divider operations.

THE FOLLOWING method for obtaining speed-time and distance-time curves is a modification of that brought out by Mailloux in 1902. It is believed to possess certain merits of simplicity, speed, and directness that may make it of interest. It has proved of especial value in teaching the plotting of these curves to engineering students. Students that have struggled with the usual step-by-step process, involving rather long and tedious calculations, or with graphic methods that require the use of many sets of curves on several sheets, seem to acquire a new interest in the subject when this method is proposed.

Briefly, the method consists in drawing on the sheet of motor characteristics besides the speed-current and traction-current curves, certain so-called "service characteristics" as shown in Fig. 1 and explained below. From these curves, time and distance increments corresponding to assumed speed increments are found by a few simple divider operations. To avoid confusion, on one of the sheets are placed the motor and service curves for a limited number of load conditions, perhaps for a motor car with and without a trailer, new sheets being readily made for wider variations in train make-up or in motor equipment.

The make-up of a sheet of curves is as follows: Motor speed-current and traction-current curves are plotted to as large a scale as possible from the records of tests. To the same scale

is plotted the train resistance-speed curve, f, from Armstrong's formula, $f = W' \left\{ \frac{50}{\sqrt{W}} + 0.03\,V + 0.002\,V^2 a\,(1 + 0.1\,[N-1]) \right\}$ wherein W is the weight of the whole train in tons, while W' is the load in tons per motor. Horizontal lines are drawn, such as g, whose constant ordinates are the pounds traction required for various grades and curves for W' tons per motor. Using the upper right-hand corner as a second origin, net traction is plotted

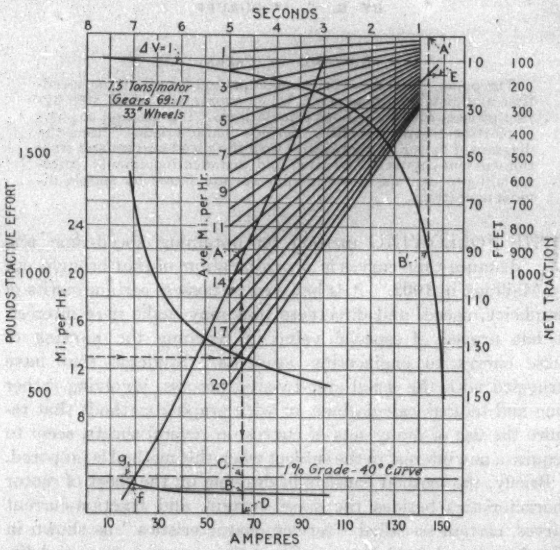


FIG. 1

downward against time increments plotted to the left, using the same scale as for the traction-current curve. This gives one or more hyperbolas whose equations are $T_n \times \Delta\,t = \Delta\,v \times 100\,W'$, wherein T_n is net traction, $\Delta\,t$ is a time increment, W' is the tons per motor, 100 is a constant including 91.1 plus an allowance for the energy of the rotating parts, and $\Delta\,V$ is a speed increment, constant for each hyperbola. From the same corner are drawn a series of radii intercepting equal distances on the

vertical lines. These radii, labelled 1, 2, 3, etc., are lines of average velocity, a scale of corresponding distance increments running downward from the corner at the right. This distance scale is so selected that projection vertically from some time division, such as 5, to a radius, such as 15, and then horizontally to the distance scale, will indicate the distance travelled, in this case 110 feet, during the selected time interval at the indicated average velocity.

To use the curves on the motor sheet, Fig. 1, to obtain the car characteristics curves, Fig. 2, proceed as follows: The points on

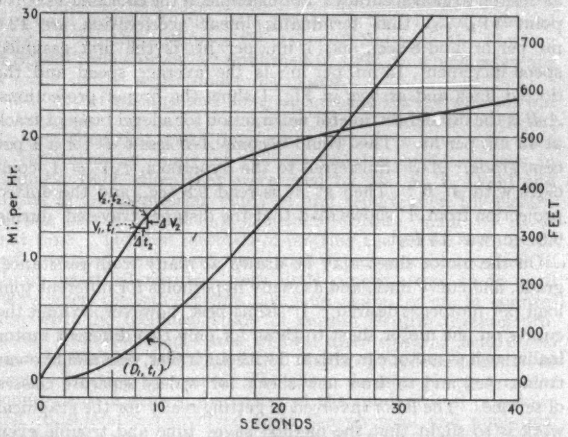


FIG. 2

the curves of Fig. 2 that mark the end of running on control (V_1, T_1), (D_1, T_1), are found in the usual way from initial assumptions. To find the point (V_2, T_2) on the speed-time curve, assume $\triangle V_2 = (V_2 - V_1)$. On the mi-per-hr. scale at the left of the motor sheet, find the division representing the average speed, $(V_2 + V_1) \div 2$. Project horizontally to the speed-current curve and from there vertically to the traction-current curve. Set one divider point on the traction-current curve and the other on the train resistance curve, f, in the same vertical line. Increase or decrease the divider setting by the ordinates of the proper grade and curve lines if necessary. Slide one di-

vider point along the axis of time increments at the upper edge of sheet, keeping the points in the same vertical line, until the other point intersects the hyperbola whose constant was the assumed speed increment. Then the first divider point indicates the time increment, $\triangle T_2$, and the second point on the speed-curve is determined. Drop vertically from the division $\triangle T_2$ on the time increment scale to the radius labelled with the average speed, $(V_2 + V_1) \div 2$ and read the corresponding distance increment on the scale to the right. Proceed thus for successive points on the car curves, changing the assumed speed increment as desired to gain accuracy. For example, if the coordinates of the point (V_1, T_1) that terminates linear acceleration are 12.5 mi. per hr. and 8 sec., and 1 mi. per hr. is the first assumed speed increment, 13 mi. per hr. is the average speed and the dotted lines and arrows in Fig. 1 show the proper projections. *A-B* is the divider setting for net traction for a level tangent track at 13 mi. per hr. This would become *A-B* less *C-D* for a 1 per cent grade. *A-B* transferred to the hyperbola, $\triangle V = 1$, coincides with *A'-B'*. Then at *A'* is read 0.8 sec., and the dotted projection from *A'* shows at *E* that the distance traveled during 0.8 sec. was 15 feet.

On the motor sheet may be drawn as many train resistance, grade, and curve lines, and as many hyperbolas for different tons load per motor, as desired. It seems best, however, to limit the curves on one motor sheet to those for only two different motor loads, such as motor car with and without trailer, one- and two-car trains, etc., and to draw new sheets for widely separate classes of service. The labor involved in getting ready for the graphical work is so slight that the method saves time and trouble even when one has to plot but a single speed-time curve for a particular motor load.

DISCUSSION ON "GRAPHIC METHOD FOR SPEED-TIME AND DISTANCE-TIME CURVES" (WOODRUFF), NEW YORK, NOVEMBER 13, 1914.

Selby Haar: In looking over this paper the thought occurred to me that since it is a graphical method it is open to the objection to most graphical methods, namely, one must be very careful in the construction if the results are to be used for anything more than demonstration purposes. These methods are quite frequently used, not so much in railway work as in some other branches of the electrical industry, for obtaining guarantees to be used in contracts, and I have found that they cannot be relied upon closely enough for such purposes.

C. O. Mailloux: The subject of Prof. Woodruff's paper is of special interest to me as a pioneer in that line of technical work. I am the author of the paper ("Notes on the Plotting of Speed-Time Curves"),* published in 1902, to which reference is made in the paper under discussion.

The art of making and using speed-time curves was not old in 1902, when my paper was written, for, as stated in the paper, the first time that speed-time curves appear to have been used in the technical study of railway traction problems was in January, 1898, when they were used by Mr. S. T. Dodd and myself in an engineering study of and report upon the electrification of the Manhattan Elevated Railway, made by us at that time. The first methods of plotting the curves were crude and laborious, and much time and patience were required to obtain practical results. Very little progress was made until 1900, when the subject was taken up again by me in connection with the technical study of certain electric traction projects. The 1902 paper was written after working nearly two years in devising and applying methods of predetermination in electric traction problems. The paper, besides giving a rather comprehensive general discussion of the fundamental principles and considerations involved from the physical and analytical standpoints, sets forth different graphical and other methods which had been devised and which had been used with satisfactory results, at that time, for plotting speed-time curves and the various other curves, especially those of train power, and energy, etc., designated in the paper as "subsidiary" curves. That paper was the first publication of any kind on the subject, and it remained, for some years, the only printed reference to it. Although it was a fairly complete résumé of the subject for its time—twelve years ago—it does not and could not, of course, set forth the developments and modifications which have become known since that time. For nearly ten years after the paper was presented, I continued to use and to develop graphical and other methods of predetermination in connection with electric traction problems. Considerable publicity

*TRANS. A. I. E. E., 1902, Vol. XIX, p. 901.

was given by me to these later developments in courses of lectures delivered each year during that period at different engineering schools, and also in some lectures delivered in Europe.

Many efforts have been made to find analytical methods of predetermination which will render unnecessary the plotting of curves of train-motion, train-power, energy, etc., as a function of time or distance. The difficulties to be overcome in order to accomplish this were mentioned by me in the discussion of Mr. F. W. Carter's A. I. E. E. paper ("Predetermination in Railway Work"), in 1903. I have, several times since then, had hopes of success, which were all, however, followed by disappointments; and so these curves still have to be plotted "point by point," by the aid of graphical methods like those described in my paper or by modifications of them.

The aim of all the methods and of their modifications is the same, namely, to reduce the amount of time and work required

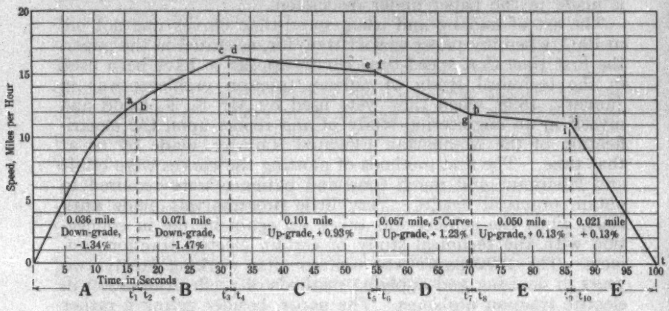


FIG. 1

to plot the curves. Now the part of the work that is most difficult and that requires the most time, is the determination of the proper precise point at which each portion of a curve ends and the succeeding portion begins. There are many conditions to be anticipated and to be taken into consideration as causes of incidental or of necessary variation of the speed of a train or a car in a given "run" between two stations. At one point there may be up-grades which limit the speed attainable; at other points, down-grades, which would make the speed rise too high; and at other points, curves, crossings and bridges which limit the speed allowable. In order to deal properly with all these independent variables, it is necessary to subdivide the total distance of a run between two stops into as many portions as there are changes in road and service conditions in that run. Take, by way of illustration, a simple run in which there are a few changes of conditions (Fig. 1). In the first

portion, A, the car, as it starts, runs on a down-grade of 1.34 per cent for a distance of 0.036 mile; it then comes to a portion, B, 0.071 mile long, where the down-grade increases to 1.47 per cent, which causes the acceleration to increase instead of diminishing; after that it comes to a portion, C, 0.101 mile long, on which there is an up-grade of 0.93 per cent; on the next portion, D, 0.057 mile long, there is an up-grade of 1.23 per cent, and a curve of 5 degrees; the power is shut off and the car is allowed to coast so as to reduce the speed; on the last portion, E, 0.071 mile long, the up-grade reduces to 0.13 per cent, and the car can continue to coast with less retardation than on the previous portion, because the road is nearly level, until the point is reached, E', where the brakes must be applied to bring the car to a stop. The great difficulty, the time-consuming process, comes, as I already said, in finding where to cut these portions of a run, A, B, C, D, E, E', and in joining them properly together. The diagram, when completed, (and, by the way, I prefer the term "velocity-time diagram," or else "V-T-graph" to "speed-time curve"), must satisfy an important mathematical condition, which is, that the area corresponding to any time-interval whatever between the beginning and the end of the run must be in definite and precise proportion to the distance passed over during that time-interval. This condition is expressed symbolically by a definite time-integral, thus:

$$S = K \int_{t}^{t'} v dt$$

where S = the distance passed over in the time-interval $t - t'$
v = the velocity or speed at any instant of time, t.
K = a constant depending upon the scale of the diagram and the units of measurement employed for velocity, time, and distance.

$= \frac{1}{L}$, where L = a "scale-factor"

Now this expression is nothing more nor less than the equation of the so-called "*distance-time curve*." The quantity indicated by this definite integral is nothing more than the area of the diagram or portion thereof comprised in the time-interval $t - t'$, whether this time-interval be that of the whole run, or of any portion of it. The distance-time graph (which may be also termed "space-time" or "S-T" graph) plays a controlling role in the construction of the V-T graph. Indeed, the V-T graph could not be made accurately, if at all, without the information which the S-T graph alone can furnish. Unfortunately, the construction of the S-T graph requires the use of some method of integration, either mechanical or graphical, and this is the very part of the whole work which almost every-

body has found most difficult and tedious. The reason for saying "*almost*" everybody will be given presently. Those who sought to remove the difficulties soon realized that it was not possible to do away altogether with the distance-time graph, and that the most which they could hope to accomplish was to make a simpler and cruder form of *S-T* graph answer the purpose. The characteristic and seemingly novel feature of the paper presented this evening is an effort in this direction.

As the method of plotting described in this paper is an offspring of the ideas and methods set forth in my 1902 paper, we may begin by considering the points of resemblance and of difference between them.

We will first refer to and compare the means used for finding "points" in the *V-T* graph, for plotting that graph; and we will then compare the means for finding the distances corresponding to the different time-points in the *V-T* graph.

Those who are familiar with this subject, and with the use of the charts of "Coefficients" and of "Reciprocals," described and illustrated in my 1902 paper (Figs. 9 and 10), will easily see that the same principles are utilized in the construction of the "chart" shown in Fig. 1 of this paper. The theory of this portion of the method is the same in both cases. There are some modifications in details, which presumably were intended as improvements. Two of these deserve mention. The first one consists in drawing the curves of reciprocals (hyperbolas) on the same chart as the curves of tractive efforts corresponding to motor-power, grades, train-resistance, instead of drawing them on a separate chart, as recommended in my paper. This, it happens, is just what I did myself at first. I soon found, however, as others surely would, when working continuously for weeks and months at a time, in plotting *V-T* and other time-function graphs of train-motion, that while one may need and may have to prepare many dozens of different charts of tractive efforts and acceleration coefficients to serve for different motors, gear-ratios, voltages, train-weights, etc., and also for different service-conditions, one single set of hyperbolas ("reciprocals"), on a separate sheet, will suffice and will serve perfectly well for all the charts of coefficients, and even for several persons working on this kind of work; and that, consequently, the reproduction of the hyperbolas on every chart is a pure waste of time and effort.

In passing, I may say that the idea of "lumping in" the kinetic energy due to rotative parts by using 100 instead of 91.1 as a constant, is not to be recommended for accurate work, in view of the fact that this kinetic energy is never constant, and may have values ranging between 3 per cent and 11 per cent. It is better, in my opinion, to make the correction for rotational kinetic energy separately, and to make it correctly, for each case, especially as it can be done very easily indeed on a "Chart of Coefficients" made as shown in Fig. 9 of my paper, by the

addition of one line. The second modification consists in replacing the curve of tractive effort as a function of the speed (curve M in Fig. 9 of my 1902 paper) by two other curves, one giving the speed, the other the tractive effort, as a function of the *current*. Now, it is precisely from these two curves (which are shown in Fig. 5 of my paper) that the curve M in Fig. 9 of my paper is derived; and these two curves, as used in the method described in the paper before us, serve identically the same purpose, namely, to give the *tractive effort* as a function of the *speed*. Hence, there is really no difference in the fundamental principle. The theory remains exactly the same; only, in my case, the work of obtaining from the two curves in question the values of the tractive efforts as a function of the speed is performed at the outset, once for all. The curve of these values, which is, by the way, a very important and useful curve, is plotted on the chart itself; whereas the author of the paper has to obtain the values of tractive effort from the two current-function curves for each point of the V-T curve, which makes the work of using the chart and the chances of error both greater. There are at least two practical objections to the innovation; first, two distances have to be measured, one horizontally, the other vertically, to obtain the value of gross tractive effort corresponding to any speed, prior to subtracting the loss due to train-resistance and upgrades, or to adding the gain due to down-grades (an operation which requires still other measurements, and, consequently, introduces more possibilities of error), whereas the curve M of the chart of coefficients (Fig. 9 of my paper) not only gives the desired values directly for all speeds so they can be read off without dividers, but it even enables the sum or difference of the tractive efforts in question to be read off or measured directly at one operation; second, it is not possible with the chart shown in Fig. 1 of this paper to determine at a glance, as can be done so easily by means of the chart shown in Fig. 9 of my paper, the point of zero acceleration, and, consequently, the maximum speed attainable under any and all conditions of grades and train-resistance, also to determine the acceleration or retardation which will occur on any given grades, etc., and to answer various other questions which the chart of coefficients can answer readily and accurately by the curve M and the curve N (net tractive effort) as shown in my paper. The fact is that the curves M and N give an actual graphical representation of quantities which are of immediate interest and importance, namely, the "gross" and "net" tractive efforts as a function of the speed; whereas the two curves from which the curve M is derived give graphical representations of functions which are not of immediate but only of remote or incidental interest. In addition to this, the use of the curves M and N makes the operation of finding the points for plotting the V-T graph simple and more accurate than the method represented in Fig. 1 of the paper. The practical value of the modifications just considered does not, therefore,

appear to be obvious. To me it appears, on the contrary, quite doubtful.

A word of caution may be added here about taking train-resistance formulas at their "face value", or without discount or comment. Experience has demonstrated long ago that "circumstances alter cases" very greatly in train-resistance; and that the formulas often require considerable change in form and in coefficients to make them suitable for different cases. A glance at the formulas mentioned in the paper shows readily to an experienced person that it is best suited for interurban lines running at high speeds on first-class tracks, and wholly unsuited for lighter cars or trains run at lower speeds, on city tracks. In practise it is necessary to use *several* curves of train-resistance for the same motor-equipment per car or per train. Several sets of curves of tractive efforts and train-resistance may be drawn on the same chart. I have drawn as many as eight sets on the same chart of coefficients; but, as a rule, it is not desirable to put more than two or three sets on the same chart. It is better to make new charts, which is a very simple matter when blank charts are prepared beforehand, as recommended in my paper.

The portions of the chart shown in Fig. 1, so far considered, relate to the process by which speed-time curves (or *V-T* graphs) are plotted by a "point-by-point" process. In summing up what has been accomplished in connection with this portion of the subject in the last thirteen years, I feel quite warranted in making the statement that all the methods of "point-by-point" plotting of *V-T* graphs which have proved satisfactory and practical are based upon and embody the ideas and the essential features set forth in my 1902 paper. At any rate, although I have kept in close touch with this work, I have yet to learn of a successful method which is not patterned on the lines therein suggested; and, usually, the modifications, if any were made, were not of material importance or advantage. Most of those who have done work and who have written on this subject have acknowledged the original source of the ideas and features adopted. In other cases there has been a seemingly studied silence on that score; and I have had the interesting experience of seeing my own methods, with practically no modification or disguise, explained to me by persons who had learned about them in Germany and believed that they had—in fact must have—originated there. It was a case where the label "Made in Germany" should have read "*Copied* in Germany, from the original American model".

We come now to the operation of cutting off *V-T* graphs, or portions thereof, at the proper time-points. We find here a marked divergence in views and in methods. The methods described in my 1902 paper involve the accurate mechanical integration of the actual *V-T* graph, and the drawing of its integral-graph—the distance-time graph—which is represented

by the equation to which reference was made a few moments ago. The method shown in Fig. 1 of the present paper aims to obtain the time-points of distances by a process of graphical integration of a modified and simplified *V-T* graph, in which the instantaneous velocities during a certain time-interval are replaced by an "average" velocity for that time-interval.

While this part of the work, as already stated, has been found very difficult and tedious by *almost* everybody, yet, paradoxical as it may seem, it is regarded by others, including myself, as being the easiest and most interesting part of the whole work. The explanation of this difference is simple enough. It is the difference, merely, between, on the one hand, trying to dodge or shirk the task of performing an operation of integration, and, on the other hand, making arrangements to do it very accurately while doing it easily and quickly—it amounts to a question of the facilities available for the mechanical integration of the *V-T* graph, and for drawing its integral line—the distance-time graph. Where the proper integrating facilities are available, there cannot be the least doubt that the most accurate, as well as the easiest and quickest method of finding the definite time-points which correspond to given and determinate distances in *V-T* graphs, is by drawing the integral lines of these *V-T* graphs and by making use of them in the manner set forth in my 1902 paper. All those who have done the work or who have seen it done in the proper manner by this method, understand fully why the work is both easy and interesting, and why the method is both rapid and accurate; and they also can see the drawbacks and difficulties of all methods which aim to simplify the integral-line of the *V-T* graph or to avoid drawing it.

I realized at the outset, in entering upon this work, the importance of having at hand a satisfactory integrating apparatus by whose aid integral lines could be obtained quickly and accurately. Fortunately, such an apparatus was already available in the form of an integrating instrument called the "integraph", which, as stated in my 1902 paper, "in addition to giving the numerical results of the integration, actually shows the steps of integration graphically by drawing the so-called 'integral' line". The time required to draw, with an integraph, the integral line corresponding to any area is no greater than that required to follow with the tracing point of the instrument the outline of the diagram to be integrated. The "scale" of the integral line can be as easily varied as the "scale" of a planimeter, so that it is easy to adapt the area-units exactly to any coordinate paper, and even to make corrections for the difference in various papers due to shrinkage, humidity, etc. The integraph is in every sense an instrument of precision as well as a great time and labor saving device, of the highest value in work of this kind. In one series of predeterminations made under my direction, covering a period of about six months, one integraph saved over ten times its cost, and greatly shortened the time

required for the work, besides adding very greatly to the precision of the work done. It is by the aid of this wonderful instrument that the otherwise difficult and tedious tasks are rendered easy and interesting. It is important to bear in mind that there are other integrations to be performed besides that of the *V-T* graph, for which the integraph can be also used to great advantage. As is well known, the *V-T* graph itself is, in reality, merely what might be termed the foundation and scaffolding for the structures which are of real importance and significance, namely, the "subsidiary" curves, like those of current and power input, energy, etc. Now the energy-time curve, representing kw-hours, is the integral curve of the power-time curve representing kw-input. In Fig. 5 the energy-time curve, shown on the upper part of the diagram, was drawn directly by the integraph by the integration of the kw-input curve which is shown on the lower part of the diagram. The curve was drawn in a few minutes, whereas it would have required several hours to obtain the same curve by any other process of integration, with probably much less precision. The utility of the integraph does not end here by any means. For determining, from the current-input curve, the equivalent "heating" current, or the r.m.s. value, it is a most valuable labor-saving appliance. The manner in which the integraph is employed for such predeterminations will be found described in a special paper on that subject, presented by me at the Turin Electrical Congress in 1911 (see Proceedings of Turin Electrical Congress, II, pp. 990-1016). A graduate-student who attended one of my courses of lectures and of drafting-room instruction and exercises in predeterminations by the aid of the integraph, informed me at the end of the term that he had done easily in less than two weeks more and better work than he had been able to do in about two months some time before, while employed on the same kind of work in the railway engineering department of one of the large companies. This is a fair sample of the results which indicate that the best method is the cheapest. Usually those who have this sort of work to do have enough of it to make it economical to use an integraph as a time and labor saving device, besides improving the quality and precision of the work done.

I have with me some specimens of *V-T* and other graphs that show the kind of work done by my methods with, of course, the aid of the integraph, which I consider indispensable for high-grade work. I also have some diagrams specially prepared to illustrate certain points in the comparison of different methods.

I will first show how easily the operation of cutting off and joining portions of a *V-T* graph can be performed by the aid of the integral-graphs drawn by the integraph. I will describe the process whereby the different portions (A, B, C . . . E') of the *V-T* graph already referred to (Fig. 1) were constructed and joined together. Fig. 2 shows the details of construction for portion A only. Fig. 3 shows the details for all the portions.

Starting with portion A, the first step was to find the co-ordinates of a certain number of points for this portion of the graph. This was done by the use of charts of "coefficients" and of "reciprocals" in the manner described in my paper. The diagram of acceleration and retardation coefficients used must, of course, be that suited for the particular motor-equipment and service-conditions of the case; and it must be specially prepared when not already "in stock". In an office where much of this work is done, the stock of graphs of acceleration and retardation coefficients is being constantly increased by additions made from time to time to meet new conditions and requirements, such as changes in type and size of motors, or in h.p. and tractive effort available per ton of train, also changes in gear-ratio, voltage, etc., and changes in train-resistance due to difference in track conditions, length and weight of train, etc. If all the charts of coefficients prepared are preserved they constitute, in time, a large assortment of charts covering a great range of conditions and requirements. As already stated, only one chart of reciprocals is necessary for any and all the charts of coefficients, provided the latter are all made to the same scale.

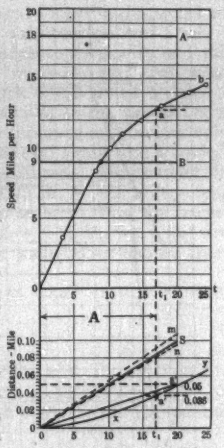


FIG. 2

Using a chart containing the proper curves of acceleration and retardation coefficients, *i.e.*, the proper curves of motor tractive efforts and train resistance as a function of the speed, and proceeding in the simple manner explained in my paper, the co-ordinates for the initial portion of a V-T graph are then found for portion A, which, as the data given on the diagrams indicate, (Figs. 1 and 3) is on a "down" grade of 1.34 per cent. While each point may be plotted from its co-ordinates as soon as these are obtained, it saves time to defer doing it until the co-ordinates for a number of points have been obtained. When several persons are employed on the same work, one may find the co-ordinates while another plots the graphs. The points for which co-ordinates were obtained in this case are indicated by small circles. The co-ordinates are determined so easily and so rapidly that there is no objection to plotting the graph considerably beyond the point at which a rough estimate indicates that the portion will end. The V-T graph for the portion A was plotted only a short distance beyond the right point a in Fig. 2, but a considerable distance beyond that point, b, in Fig. 6.

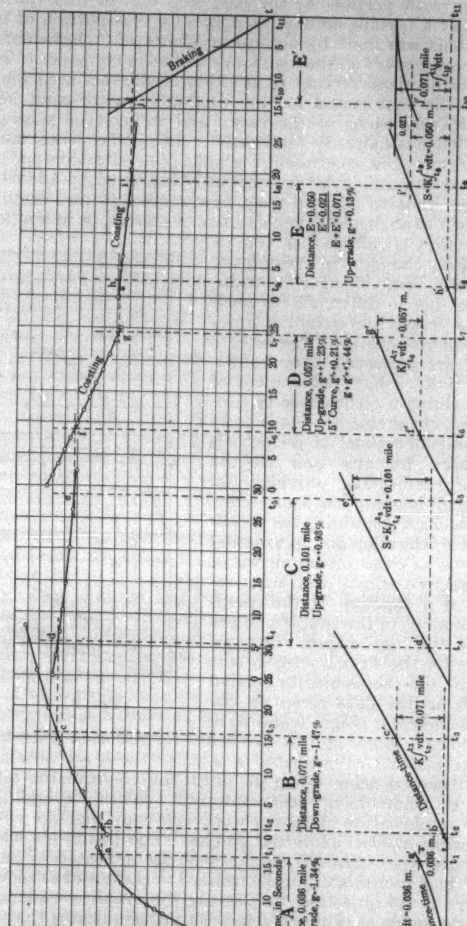

Speed.-Miles per Hour (v)
Time in Seconds
Distance.-Miles
Coasting
Coasting
Braking
A
Distance, 0.036 mile
Down-grade, g=-1.34%
B
Distance, 0.071 mile
Down-grade, g=-1.47%
C
Distance, 0.101 mile
Up-grade, g=+0.95%
D
Distance, 0.057 mile
Up-grade, g=+1.29%
E
Distance, E=0.050
E'=0.021
Up-grade, g=+0.13%
E'
0.071 mile

FIG. 3

After a portion of V-T graph of more than sufficient length has been plotted and drawn, in pencil, the next step is to find the point a, at which the portion A ends. We begin by adjusting the integraph to the desired scale, so as to obtain an integral line whose ordinate at any time-point, when measured by a scale, will give the exact distance covered, up to that point. When the same co-ordinate paper has already been used, and the scale-factor for the integraph is known, the adjustment can be made directly. When the scale-factor is not known, the proper adjustment may be obtained by drawing, a number of times, the integral curve for a certain definite area of V-T graph corresponding to an exact distance, and varying, each time, the adjustment, until an integral graph is obtained of the exact scale desired. In Figs. 2 and 3 the scale used for ordinates was 1 mi. per hr. = 0.2 in., and the scale used for abscissas was 1 sec. = 0.1 in. A distance of 1 mile corresponds to a velocity of 1 mile maintained during one hour (3600 mi-sec.), and this would correspond on the V-T graph to an area of $0.2 \times 0.1 \times 3600 =$ 72 sq. in. The same area, for a velocity of 18 mi. per hr., or an ordinate height of 3.6 in., would correspond to an abscissa value of 200 sec. or 20 in. Taking a distance of 0.1 mile and a velocity of 18 mi. per hr., the time required is 20 sec. The scale of distance adopted in Fig. 2 and 3 was 1.25 in. = 0.1 mile; hence the integraph required to be adjusted so as to draw an integral line whose ordinate at $t' = 20$ sec., is = 1.25 in. when the area integrated is exactly 7.2 sq. in. The scale-factor should therefore be $= \frac{7.2}{1.25} = 5.76$. This means that in the equation

$$S = K \int_{t}^{t'} v dt$$

when $S = 1.25$ and V and T are both expressed in inches, then $K = \frac{1}{L} = \frac{1}{5.76}$ if the co-ordinate paper used is accurately divided and requires no correction. In most cases some correction is required, as the co-ordinate paper or tracing cloth used is seldom exactly right; and the precise values of K will be either greater or smaller than the theoretical value.

In Fig. 2 the inclined right line $O\ S$ in the lower part of the diagram is the integral line or graph which was drawn by the integraph when its tracing point was moved, in the upper part of the diagram, along the lines O-18, 18-A and A-20, which represent a V-T graph of constant velocity = 18 mi. per hr., and when the scale-factor L of the instrument was exactly right for the co-ordinate paper used. The ordinate of this integral line at $t' = 20$ is exactly equal to 0.1 mile by the scale of distance. The V-T graph of constant velocity = 9 mi. per hr.,

gives an integral line OS' of half the slope of OS. The inclined lines Om and On show integral lines obtained instead of OS when the scale-factor, L, was respectively lower and higher than the correct value. As it only requires the movement of an adjusting screw to change the scale-factor and to draw a new integral line, the correct value of L can always be found very readily. The time required to make the adjustment is less than that required to describe it. In practise, the adjustment often remains unchanged for days and weeks at a time. After the instrument has been properly set for the paper and the scales employed, the next step is to integrate the actual V-T graph Oab (Fig. 2), and obtain its integral graph Oxy. Having done this, a horizontal line is drawn through the integral-graph at the ordinate height corresponding to the actual distance of portion A of the run, which is 0.036 mile. The abscissa of the point a', at which the horizontal line intersects the integral-line, represents the time at which portion A of the run ends; and a vertical line a'-a drawn through a' will cut off the V-T graph exactly at the end of portion A. The process of cutting off the portion A is seen more clearly in Fig. 3, in the lower portion, where only the integral-graph actually necessary, Oa', is drawn. The whole operation only requires a few moments.

The next step is to obtain the co-ordinates for a number of points for plotting the second portion B of the V-T graph. The process for obtaining the co-ordinates is substantially the same as for portion A. In this case the up-grade increases to 1.47 per cent, and the distance is 0.071 mile. We can start plotting the curve anywhere on the sheet, beginning with a speed that is somewhat under the speed at the end of the portion A. A portion of V-T graph is then plotted, counting time-values from the first speed-point used. The portion B, as shown in Fig. 3 begins with the speed of 12.3 mi. per hr., and continues until the speed of 19 mi. per hr. is attained (in about 33 seconds). After the points have been plotted, and the graph has been drawn, the integral-graph for the whole portion plotted is drawn by means of the integraph; and the operation of cutting off, from the portion plotted, the precise part and portion required for portion B of the V-T graph, can then be performed very easily. As portion B is a continuation of portion A, the speed at its beginning must be *exactly* the same as the terminal speed of portion A. This speed, and the starting points of portion B are both easily found by the very simple operation of drawing through the end of portion A, at "a," a line parallel with the axis of time, to intersect the second portion of graph at b. This point of intersection b is the proper beginning of the portion B of the run. From this point a vertical line drawn downward, b-b', to intersect the second integral-graph, gives the "lower limit" b' of the definite integral representing the distance-time curve for portion B. To obtain

the "upper limit" of the integration required, a line parallel with the time-axis is drawn through the point b', and from this line as a base a vertical distance is marked off, equal, by the scale of distance, to the actual distance for portion B; and another line drawn parallel with the time-axis through the upper part of the distance just marked off, intersects the integral-graph at the point c' corresponding to the "upper limit." A vertical line c'-c, drawn upward from c', to intersect the V-T graph, cuts it off at the proper ending point c. The portion b-c is all that is needed for portion B of the V-T graph. If desired, the useful portion can now be shifted to the left, so as to bring the point b on the point a, thereby joining the portions A and B together. All that is necessary is to transfer the plotted points of portion B to the left by means of dividers to a distance equal to a-b. A new portion of graph can then be drawn, by means of these points, and the other graph being no longer necessary, can be erased. If desired, the useful portion of the integral-graph can also be shifted so as to form the continuation of Oa' from the point a'. As a matter of fact, the easiest and quickest way of making the shift is to integrate the useful portion b-c after its transfer, placing the integraph pencil or pen on the point a', so as to make the integral line start from that point. The integraph will then draw the portion B of the integral graph in the correct relation with respect to that of portion A.

Another plan is to leave the different portions of the run separated and to "assemble" them afterwards on a "tracing." This plan usually takes less time than the other.

The process of plotting, drawing, and cutting off the useful portions of V-T graph for portions C and D is substantially the same as for portion B. In portion C the train, though running with power, is losing speed, because it is on an up-grade. In portion D the power is cut off to reduce the speed, on account of a curve which exists on this portion of the run. In portion E the coasting continues on a nearly level track until a point is reached where the braking must begin in order to bring the train to a stop. Now the portions E and E' together represent the final portion of the run, which is 0.071 mile in length. The important point is to find out the exact time at which the braking must begin. This operation, which is usually very difficult by other methods, is rendered very easy by the use of the integraph. As the rates of retardation attainable by braking are known, the "slope" of the braking portion of the V-T graph is also known. This portion can be drawn "backwards" from any convenient point. The coasting curve for the earlier portion E of this part of the run is plotted "forward" in the usual way from any convenient point, and its integral-graph is drawn by the integraph. After the portion D has been properly cut off at both ends, its final point g determines the initial point h of the portion E by means of the horizontal line g-h in the manner already explained. The point h in its turn de-

termines the point h' which is the lower limit of the useful portion of the integral-line for portions E and E' together. The upper limit is then obtained by drawing a horizontal line at the proper distance (0.071 mile) above the line through h'. Now by integrating the braking curve "backwards" from the line of upper limit, the integral-graph of the braking curve will be drawn *downwards* from this line. Any horizontal line drawn between the upper and lower limits will intersect the integral lines for portions E and E'. The distance from this line to the lower limit will correspond to the distance for portion E and the distance to the upper limit will correspond to the distance for portion E'. Now there is only one particular "level" at which this line will be correctly located; and this level is found quite easily by the aid of the two integral-graphs. We may begin by drawing a horizontal line at any level, between the two limit-lines. Through the points of intersection i, j, of this line, with the integral curves $h'i$ and $j'k$, vertical lines $i'i$ and $j'j$ are drawn to intersect the corresponding portions of the V-T graph. Now if the points intersected i, j, by these vertical lines are at the same level, so that they can be joined by a horizontal line, then the line i' j' was located at the proper level; if not, the line $i'j'$ must be changed to a higher or lower level until the points i, j, come to the same level. Usually the proper location for the line $i'j'$ is found by two or three trials. In this case the correct location makes the coasting portion, E, 0.050 mile long, and the braking portion, E', 0.021 mile long. The different portions may be "assembled" on the same sheet, by displacing or shifting their useful portions to the left in the manner explained in connection with portion B. The easiest way to "assemble" them is by the operation of "tracing" from a sheet, like that shown in Fig. 3. The "tracing" of the completed V-T graph is as shown in Fig. 1.

Although it is more natural and usually more convenient to begin the plotting of a V-T graph by the initial portion, yet it will be possible to begin the plotting at any other portion. In fact, each portion could be plotted on a separate sheet, and by a separate individual. The objection to this would be that it would be necessary to plot a much longer portion, because it would not be so easy to determine between what speed limits the "useful portion" of the V-T graph is likely to come. It is, however, often necessary to plot certain small intermediate portions of a run by themselves, and also to do some plotting backwards. The necessity for this is apt to occur for portions of a run where bridges and sharp curves occur, and where it is necessary to coast or put on the brakes in order to reduce the speed, so as to keep it below the limit allowable. A case of this kind is illustrated in Fig. 13 of my 1902 paper. It is in cases of this kind that the superiority of the method just described over all other methods becomes evident.

The run just considered is of simple character, as compared with most of the runs which are typical of actual service con-

ditions. The conditions were arranged so as to give somewhat abrupt changes of acceleration and retardation at the points where the intermediate portions *C*, *D*, *E*, are joined together, so as to make the process of cutting off the portions more easy to illustrate. Figs. 6 and 5, reproduced from one of my lectures, show the details and the completed curves worked out in more "professional" manner, although the details are not completely given in Fig. 6. The complete *V-T* graph in Fig. 5 was traced from the "portions" as worked out on Fig. 6. The distance-time curve was drawn in pencil by assembling the "useful" portions as shown in Fig. 6, and the whole curve was then "checked up" by integrating the completed *V-T* graph in Fig. 5, and drawing the integral curve in ink by the integraph, with the result that the total error for the whole *V-T* graph was less than the thickness of the integral-line. This fact is mentioned as an illustration of the degree of precision obtainable with an integraph in good condition and used intelligently. The power-time (or kw-input) curve was plotted by reference to the completed *V-T* graph in Fig. 5 and it was then integrated by the integraph, producing the energy-time curve (kw-hr.). From this curve the energy consumption per train, per car-mile, and per ton-mile, were calculated, as given on the sheet. The operation of plotting the power-input curve is greatly facilitated by making, first, a chart which shows the power (kw.) as a function of the speed. With the aid of such a chart, the whole operation of plotting the power-input graph is performed in a short time by the use of dividers. The dividers are first set on the *V-T* graph to the actual velocity at a given time-point. The dividers are then transferred to the kw-velocity chart. The kw-input corresponding to that particular velocity is readily found and, being taken by the dividers, is transferred to the sheet on which the graph of kw-input is to be drawn. In some cases other velocity-functions, such as the power and energy expended in acceleration and the power and energy recovered in coasting, and also various other time-functions, like the power and energy expended in overcoming train-resistance and lost in the motors, are plotted on the same sheet with the *V-T* graph, and their integral-graphs are then drawn by the integraph. From these a complete analysis and segregation can be made of all the power and energy losses occurring during a run. A complete analysis of this kind, which is very simple with the integraph, has never been attempted without its aid, so far as I have been able to learn; and the simple reason is the difficulty and the great amount of work of drawing the necessary integral-graphs in any other way than by an integraph. These details, which are beyond the scope of the present discussion, are only mentioned here to show the far-reaching character of the services which the integraph can render as an instrument of precision and also as a device for saving time and labor, in connection with work of this kind.

The method of finding distances used in the paper that is before us is highly ingenious, though it is not quite new. It was

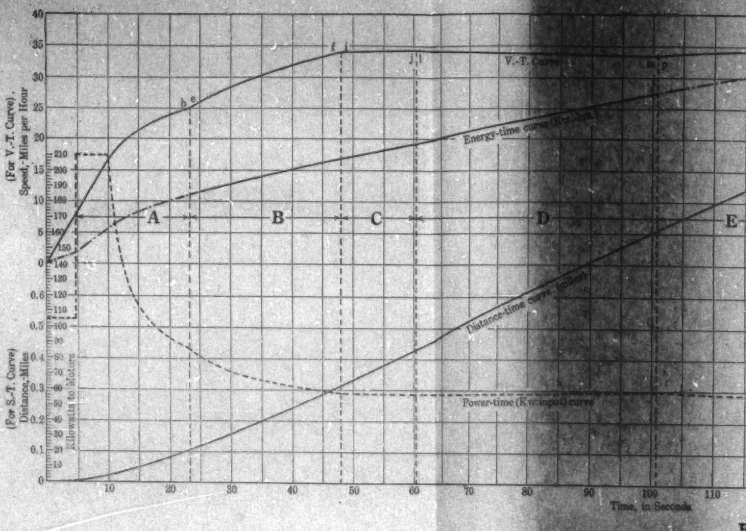
brought to my knowledge a long time ago. It has been used in Germany many years, and it may have originated there. One of the speakers this evening, who himself learned to use this method in Germany, will perhaps be able to throw some light on the origin of the method. I have never taken much interest in methods intended to replace the integraph, because of their inherent inferiority and their limitations as compared with the methods employing the integraph.

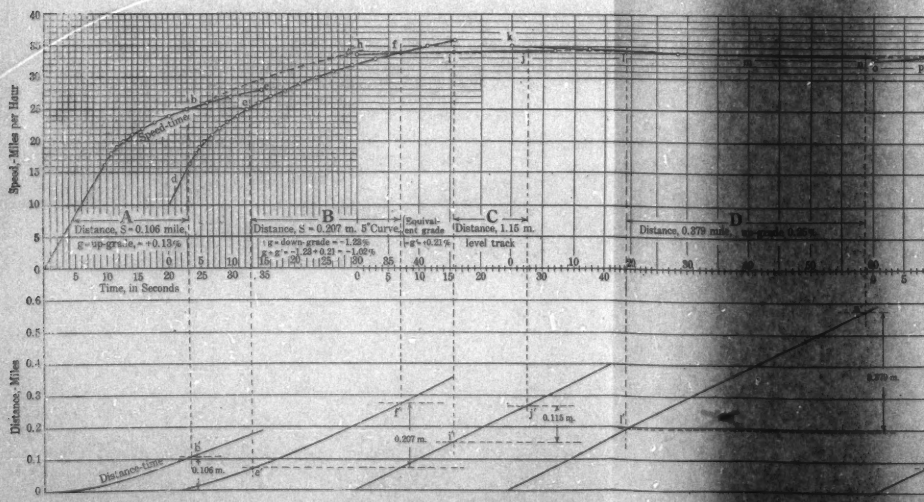
The objection to these methods is as much of a practical, as of a theoretical character. A diagram (Fig. 4) has been prepared to make this clear and to show the difference between the two kinds of methods.

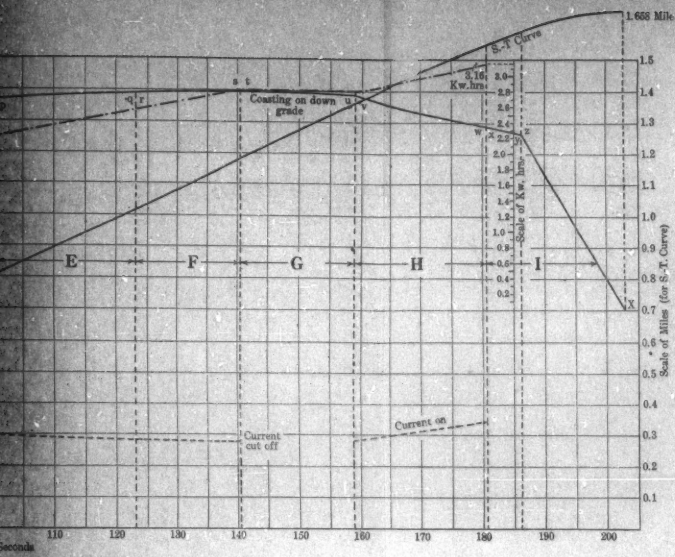
The upper portion of the diagram shows a *V-T* graph of the simplest form, comprising an acceleration period *O p q r s u v* over a distance of 0.112 mile, a coasting period (*x*, *w*) over a distance of 0.135 mile, and a braking period ($z\,t_4$) over a distance of 0.033 mile.

The middle part of the diagram shows the three integral-graphs corresponding to these three periods, and their use for cutting off the three portions of the *V-T* graph, and assembling them together into a complete *V-T* graph, in the manner already explained. The lower left-hand portion of the diagram illustrates the principle of the method used in Fig. 1 of the paper under discussion, and its application under very favorable conditions to the first portion of the *V-T* graph. The inclined lines, *O*-1, *O*-2, *O*-3, ... to *O*-16, are integral-graphs similar to the lines *O*-*s'* and *O*-*S* in Fig. 2. The line *O*-1 is the integral-graph or distance-time graph of a *V-T* graph of the constant velocity of 1 mi. per hr.; the line *O*-2 is the same thing for the *V-T* graph of 2 mi. per hr. constant velocity; and so on with the lines *O*-3, 4, 5 . . . . . to 16. The integral-graph *O*-9 in Fig. 4, which corresponds to a constant velocity of 9 mi. per hr., is the same as the graph *OS'* in Fig. 2, though it is drawn to a scale that is twice as great. These distance-time graphs are all straight lines. Each one has a constant "slope" because the *V-T* graph from which it was obtained has the same ordinate value at every point. Being straight lines, the distance-time graphs *O*-1, *O*-2 . . . *O*-16 can be drawn readily by means of a straight edge; but even this simple operation can be performed more easily and accurately by the integraph; and the graphs shown in Fig. 4 were so drawn.

In order to utilize these straight line distance-time graphs, it is necessary to modify the actual *V-T* graph, or to suppose it to be modified, in a certain way. It is necessary to assume that the actual *V-T* graph can be replaced, for the purpose of obtaining its area, by another *V-T* graph in which the speed-changes take place at longer intervals and by sudden transitions from one "average" value to another. Thus, in Fig. 4, the actual *V-T* graph, *O p q r s u v* is supposed to be replaced by the broken line *O 4 A B C D E F G H I Jv*. In that case, the horizontal line 4-*A* represents the "average" velocity between 0 and 8 mi. per hr.;


(For V.-T. Curve)
Speed,-Miles per Hour
(For S.-T. Curve)
Distance,-Miles
X Divided by 10 Above
V.-T. Curve
Energy-time curve (Kw.-hours)
Distance-time curve (Miles)
Power-time (Kw. input) curve
A
B
C
D
E
Time, in Seconds


Speed,-Miles per Hour
Speed-time
A
Distance, S = 0.106 mile.
g = up-grade = +0.13%
B
Distance, S = 0.207 m. 5" Curve.
g = down-grade = -1.22%
g = g' = -1.22 + 0.21 = -1.02%
Equivalent grade
g' = +0.21%
C
Distance, 1.15 m.
level track
D
Distance, 0.379 mile.
Time, in Seconds
Distance, Miles
Distance-time
0.106 m.
0.207 m.
0.115 m.
0.379 m.



Time of Run, 203 S
Time of Run, 0.0564 H
Distance, 1.658 M
Mean velocity, 29.4
Kw.-hours, per Train, 3.1
Kw.-hours, per Car Mile, 1.90
Train-weight. Tons, 3
Watt-hours, per Ton Mile, 54.4

FIG. 5

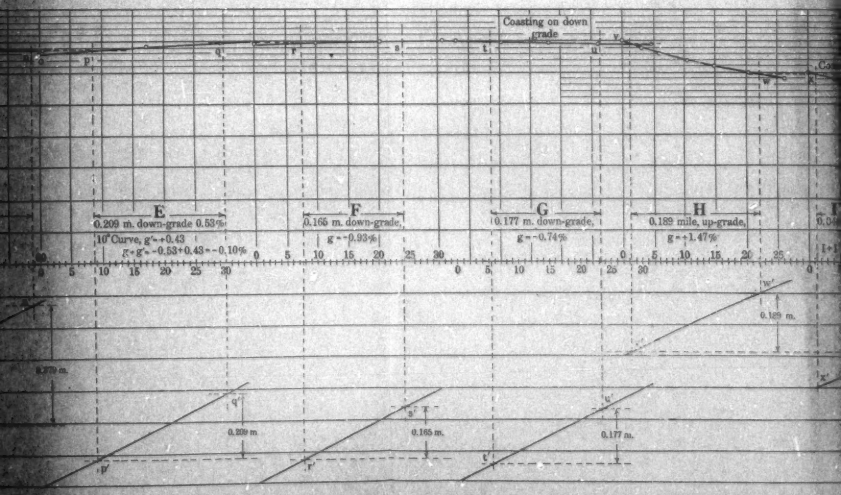


FIG. 6

and the other horizontal lines represent average velocities between other limits as follows: the line $B\,C$, the average between 8 and 10 mi. per hr.; the line $D\,E$, that between 10 and 12; the line $F\,G$, that between 12 and 13; the line $H\,I$, that between 13

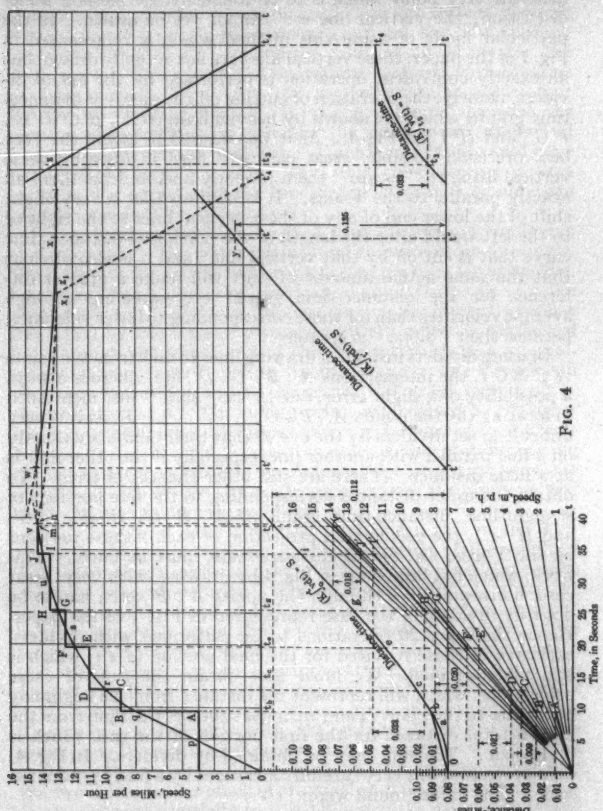


FIG. 4

and 14; the line $J\,v$, that between 14 and 14.25. The vertical line $B\,A$ is extended downward until it intersects the integral-line $O\,4$, corresponding to the average velocity $4A$ in the V-T graph. In like manner, the vertical line $D\,C$ is extended downward

to intersect the integral-line O-q, corresponding to the average velocity $B\ C$; and the integral-lines O-11, O-13.5, are intersected by the downward extensions of $F\ E$, $H\ G$, $J\ I$. As the ending point m of this portion of the run is not yet known (being, in fact, the very point which is to be found by the method under discussion) the vertical line $m\ v'$ cannot yet be drawn. In the particular mode of using this method which is represented in Fig. 1 of the paper, these vertical lines are not actually drawn, but an exactly equivalent operation is performed by the aid of dividers, namely, the operation of cutting off the pieces of distance-time graphs which are shown by heavier lines ($O\ A'$, $B'\ C'$ $D'\ E'$, $F'\ G'$, and $H'\ I'$) in Fig. 4. As it was desired to attain the very best precision possible, great care was used in drawing these vertical lines, to "locate" them properly and to draw them all exactly parallel to the V-axis. It is obvious that a very slight shift of the lower end of any of these vertical lines to the right or to the left would alter the length of the portion of distance-time curve that is cut off by that vertical line; and it is also obvious that the same actual amount of shift will make a greater difference for the distance-time graphs corresponding to high average velocities than for those corresponding to lower velocities, because their "slope" is greater.

In using dividers instead of drawing lines to find, from the points $A\ C\ E\ G\ I$, the intersections A', B', C', D', etc., there is always a possibility of a slight error, due to the "shift" just mentioned in locating the ten points A', B', C' . . . . . J', as it is very difficult to set dividers by the eye so that their points are exactly on a line parallel with another line, especially if the other line is at a little distance. There are still other chances of error. To obtain the exact distances corresponding to the five portions of straight-line distance-time graph (O-A', B'-C', D'-E', F'-G', and H'-I'), the geometrical projection of each of these portions on the Y-axis, *i.e.*, on the distance-scale, must be made. This work, which has been done in Fig. 4 by drawing, with very great care, horizontal lines through the points A', B', etc., has to be done by dividers in the case represented in Fig. 1 of the paper. Hence there are 20 operations to be performed with dividers, exclusive of those required for the final portion ($J'v'$), which is still undetermined. We must now obtain the sum of these projections, which will represent the distance from the beginning of the run to the point I; and we must subtract this sum from the known total distance for the first portion of the run, which is 0.112 mile. The sum may be obtained by dividers. In Fig. 4, each projection was very carefully measured by a finely graduated scale. The values found were:

Projection of $O-A'$	0.011	mile
" " $B'-C'$	0.009	"
" " $D'-E'$	0.021	"
" " $F'-G'$	0.020	"
" " $H'-I'$	0.033	"
Sum	0.094	"

Subtracting this sum from the total distance (0.112 mile) leaves 0.018 mile for the last part of the acceleration period of the *V-T* graph. Having decided upon an average velocity for this portion *J v*, a distance-time graph for that velocity (14.25 mi. per hr.) is drawn in the lower part of the diagram; and a portion thereof is cut off, *J′ v′*, whose projection on the scale of distance is equal to 0.018 mile. By drawing a vertical line *v′-v* through the upper end *v′* of *J′v′*, we find the point of cut-off, *m*, for the *V-T* graph. The number of operations required with dividers has been increased by at least four, making a total of twenty-four for the acceleration period. It was possible to decrease the number of operations by reducing the number of "steps" of average velocity in the modified *V-T* graph; but this would have increased the error in another way, since the difference in area between the actual and the modified *V-T* graphs would then increase materially.

Let us now compare this method with the method employing the integraph. The operation is found to be exceedingly simple. We integrate the actual *V-T* graph *O p q r s u v*, as far as we like, by the integraph, obtaining the integral graph *O a b c e g i t*. We then draw vertically from the base-line of the integral-graph a line equal by the scale of distance to 0.112 mile. A horizontal line through the upper end of this line intersects the integral-graph at the proper "ending" point *t*, and a line *t-n* drawn vertically from this point to the actual *V-T* graph cuts it off at the proper point *n*. The ending point, *m*, obtained by the other method is fairly near the correct point, *n*, because special efforts were made to secure the greatest possible accuracy by eliminating the use of dividers. When the different operations involved are performed with dividers, the difference between the points *m* and *n* may vary considerably.

The chances of error from the "modification" of the *V-T* graph would not be so great if the integration of the modified *V-T* graph were performed by the integraph, and the results obtained by one operation. This is shown in Fig. 4, where the integration of the modified *V-T* graph was actually "superposed" by the integraph upon that of the actual *V-T* graph. The straight line integral-graph *O A′* forms a "chord" to the portion *Oab*. The other straight line integral-graphs (*B′C′*, etc.) also form "chords" to the actual integral-graph, which are visible in the lower portion, but practically coincide in the upper portion. The principal difficulty with the graphical method comes in assembling the partial integrations into a complete whole. This explains the statement already made that the difference between the two methods is as much of practical as of theoretical character. It amounts substantially to this: Whereas the integraph method enables the entire integral for any portion of *V-T* graph to be obtained, and the desired value to be determined by one single operation, the same integral, when obtained by the graphical method, can only be obtained in sections, which have to be joined

together and summed up by methods which not only consume time but introduce chances of error.

The simplicity of the method employing the integraph is further shown in the coasting and braking portions of the run. A horizontal line $v\,w$ gives the "entering" speed for the coasting portion. The vertical line $w\,t'$ gives the starting point for the integral-graph $t'y$. This graph, cut off at an ordinate height equal to the proper distance (0.135 mile) gives the point of cut-off, y; and the vertical line $y\,x$ cuts off the V-T graph at the right point. A horizontal line, $x\,z$, gives the "entering" speed for the braking portion. The coasting and braking portions, when determined, are "shifted" to the left in the way already explained and as shown by dotted lines, so as to give the completed V-T graph.

In reply to the criticism made by Mr. Haar in this discussion, in regard to the accuracy of these methods, I may state in general that the accuracy is to a great extent within the control of the person making the predeterminations. I can speak from abundant experience, having seen the work done in many different ways, and I know that the percentage of accuracy depends greatly upon the person doing the work. It depends, to some extent, on the accuracy of the formulas that are used for train-resistance, upon the scales on which the drawings are made, and the precision of the methods of integration used. Where it is necessary to use average-velocity values and to determine the distance step-by-step, and especially when using dividers, one is liable to make cumulative errors, as already pointed out. These errors are eliminated if we are integrating for a whole section of line in one piece by means of an integrating device such as an integraph. So that, necessarily, a method involving the use of an instrument like the integraph is apt to be more accurate, especially if the scale is not too small and the drafting is done with some precision and accuracy, and also if the number of points determined is sufficiently great. In my lectures on the subject, I have shown the errors which result from making the "steps" or changes in velocity too large in plotting the V-T graph. It is possible to take rather large velocity-steps or changes at certain parts of the V-T graph and still have a fairly high degree of accuracy; but at other parts it is not wise to do so. In order to obtain a certain degree of accuracy, one must plot the curve with reasonable care and use a sufficient number of points. In any case, there should not be any difficulty in obtaining as close a degree of precision of predetermination by that method as by any other method used in the drafting room in electrical engineering.

N. W. Akimoff: Under the name of starting curve or archoid, the writer proposes a curve, to his knowledge quite original, the object of which is to embrace, in one equation, the peculiarities of *starting* a motor, a locomotive, an engine, etc.

The subject is so broad that only the simplest features of it will be considered in what follows.

Engineers are quite often confronted with such problems, or troubles, as, for instance, the necessity of fuses of abnormal amperage for starting a comparatively small motor; or, for example, the apparent weakness of the pins of a shaft coupling, of the ropes of an elevator, of a car coupler, of a shaft or its key, etc.

In all these instances the factor of safety, adopted in the design, may have been quite liberal, and the whole trouble arises from the fact that, in starting, this factor of safety may shrink down

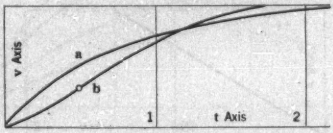


FIG. 7

to almost nothing, while being altogether sufficient for steady running.

In schools we are taught to design a shaft or a coupling for so many h.p. and so many rev. per min. without being in the least concerned as to *how it gets there.* And in dynamics we sometimes deal with problems, where the acceleration is changing *uniformly*, or, very seldom, is varying according to some prescribed law, purely arbitrary and from engineering viewpoint, meaning absolutely nothing.

Yet there are certain limitations in the phenomenon of starting,

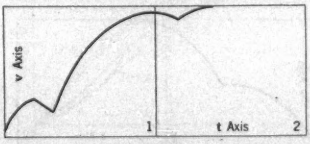


FIG. 8

certain things which *may* take place and others which *cannot* take place at all.

The proposed curve, while not at all universal, may be of considerable use in practise, both in designing and in testing machinery.

If time, t, in seconds, be taken as abscissas, and the speed, v, (in ft. per sec. or in rev. per min.) be laid off as ordinates, then the proposed equation is

$$v = N\left(1 - \frac{1}{e^{bt^2+ct}}\right) \ldots \qquad (1)$$

where N is the normal speed (linear or rotational) and b and c are constants; e being, of course, the Napierian base = 2.71828.

It is easy enough to see that, in the beginning of motion, when $t = 0$, v also reduces to zero; while after a considerable period of time, when t is very great, $b\,t^2 + c\,t$ tends to infinity, so that v reaches its normal, maximum, value, N; but t does not have to be infinite, in order that the speed may reach its full value. It will easily be seen that when the exponent, $b\,t^2 + c\,t$, equals only 4.5 or 5, the speed is already over 99 per cent of the normal; so

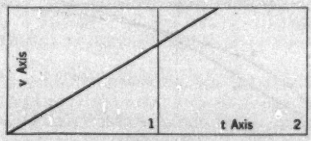


FIG. 9

that, for practical purposes, 5 or 5.5, at the most, is the maximum value required for the exponent $b\,t^2 + c\,t$. Thus, for instance, if $b = 1$ and $c = 4$, then the full speed is reached practically in one second.

This curve will be smooth in appearance (Fig. 7) as shown by a or b. In general it can be said, before any investigation has been made, that one's common sense will more readily accept this curve as likely to illustrate the true nature of starting, than for instance the fancy curve of Fig. 8, which is quite impossible, or for that matter, the curve of Fig. 9, which is rather

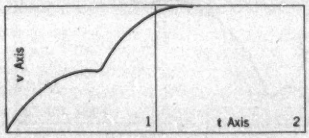


FIG. 10

improbable in practise; the latter curve, where the speed is merely proportional to the time, means that the acceleration is constant and corresponds simply to the case of falling bodies, having, as a rule, no place in the dynamics of starting. The curve shown in Fig. 10 is perfectly feasible, but it merely consists of several separate curves, each similar to that of Fig. 7.

To return to the archoid: the coefficients b and c are not necessarily positive, but cannot be both negative at the same time; one of them can be 0; if $b = 0$, we have what may be called the *simplified* curve, in contradistinction to the *complete*

curve, in which either c alone is $= 0$, or both b and c differ from zero. A very great variety of curves may thus be derived, depending upon the values of the constants b and c.

The simplified curve

$$v = N\left(1 - \frac{1}{e^{cl}}\right) \ldots \tag{2}$$

for $c = 0.5$, 1, 2 and 5, is given in Fig. 11. The complete

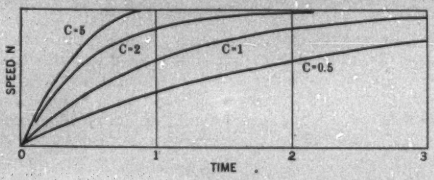


FIG. 11

curve is shown in Fig. 12; here b has been taken as $= 1$, while c has been given values 0.2, 0.5, 1 and 1.2.

The simplified curve may answer in a great variety of cases; its layout is particularly easy, especially if a table of multiples of the common logarithm of e, say from 1 to 100, has been computed once for all ($e = 2.71828$; its common log $= 0.43429$). The slide rule can be used for calculations. The simplified curve cannot have any points of inflection.

The complete curve may or may not have a point of inflec-

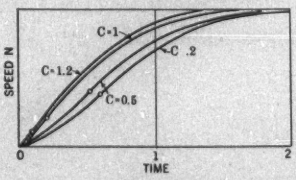


FIG. 12

tion, regarding which a few remarks will now be made. We know from the elementary calculus that, in order to have a point of inflection, the second derivative must vanish. This, in our case, leads to the quadratic expression

$$4\,b^2t^2 + 4\,bct + (c^2 - 2b) \ldots\ldots \tag{3}$$

If this $= 0$, the roots are $= \dfrac{-c \pm \sqrt{2b}}{2b}$. Hence, if the curve is to have a point of inflection, b cannot possibly be

negative. If c is positive, there will be only one point of inflection, namely, if $\sqrt{2b}$ is greater than c. If c is negative, there might be one point of inflection, *i.e.*, if c is less than $\sqrt{2b}$; or, if c is greater, in absolute value, than $\sqrt{2b}$, there will be two points of inflection.

Thus $b = 2$, $c = -3$, will mean that there are two points of inflection, at $5/4$ and $\frac{1}{4}$; while $b = 2$, $c = -1$, will mean only one point of inflection, *i.e.*, at $t = \frac{3}{4}$. If, however, the expression (**3**) is not $= 0$, there cannot be any points of inflection. The great importance of the points of inflection will become more apparent after their dynamical meaning is explained.

Prior to that we will say a few words regarding the acceleration as given by our curve. It will be readily understood that the first derivative of (**1**), or, which is the same thing, the tangent of the angle α, (Fig. 13), represents the accelera-

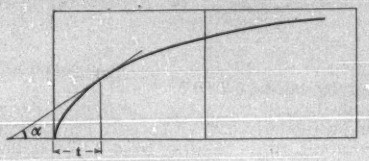


FIG. 13

tion of motion as characterized by the curve. The analytic value of the acceleration is, therefore,

$$a = N \frac{2\,bt + c}{e^{bt^2+d}} \cdots\cdots \tag{4}$$

which, for the simplified curve ($b = 0$) becomes

$$a_s = N \frac{c}{e^{d}} \cdots\cdots \tag{5}$$

The Fig. 14 shows the acceleration curve for a simplified curve ($b = 0$, $c = 1$); while Fig. 15 gives the acceleration curve for a complete archoid ($b = 1$, $c = 0.5$).

One point of inflection means the maximum acceleration, while two points of inflection mean, in our case, that at least one of them will correspond to maximum acceleration.

We will easily realize that the archoid cannot be tangent to the axis of v at $t = 0$, since this would mean infinite acceleration, which no machine could stand. On the other hand, it will be readily understood that it is perfectly feasible to have maximum acceleration not at the beginning of the motion, but somewhere between the beginning and the time at which the full speed is reached.

It is of extreme importance for a practical man to know when this occurs and to have an idea, even if only approximate, as to the value of the acceleration. Only having these data in mind can the designer lay out a machine in which the factor of safety will not be lower, at any time, than the value originally intended. Any other "assumption" is mere guesswork. It will of course be remembered, that linear acceleration, if multiplied by the mass, gives the acting force; while, in rotary motion,

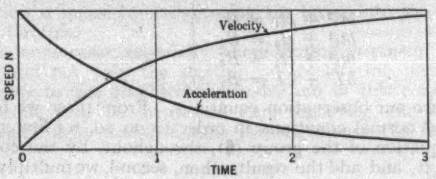


FIG. 14

the angular acceleration, when multiplied by the moment of inertia, gives the acting torque (or moment) at that time.

In practise, the only difficulty will be the finding of the constants b and c. They cannot be very well figured out and will have to be determined from tests of machinery of similar types. In order to facilitate matters it will be of advantage to remember that the area of the archoid (Fig. 16), for any time t, represents the space (linear or angular, according as we have trans-

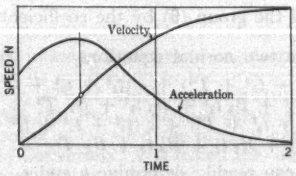


FIG. 15

lation or rotation) traveled since the beginning of motion. In practise it will be found much easier to measure this than the actual velocity, corresponding to the given time t. This remark may help to find a few of the values of v, say v_1, v_2, v_3, corresponding to time t_1, t_2, t_3; remembering, also, that we have, at the end of the starting period, (when the full speed has been reached) v = say N and $t = T$, we thus have several (say four) sets of data, from which to determine b and c.

Using the elementary rules of the theory of least squares

we now proceed as follows: let us denote $b t^2 + c t$ simply by A, so that $v = N\left(1 - \frac{1}{e^A}\right)$. . . . [see (**1**)], whence $A = \log_e \frac{N}{N - v}$ =, say, B.

Now, from our observations, we have the so-called observation equations, corresponding to various values of t and v, as for instance t_1, v_1; t_2, v_2; t_3, v_3; and, finally, T and N.

Thus we have $A_1 = B_1$; $A_2 = B_2$; etc. etc., or

$$\left.\begin{aligned} bt_1^2 + ct_1 &= B_1 \\ bt_2^2 + ct_2 &= B_2 \\ bt_3^2 + ct_3 &= B_3 \\ bT^2 + cT &= B_T \end{aligned}\right\} \quad \ldots \qquad (\mathbf{6})$$

These are our observation equations. From these we form the so-called normal equations: in order to do so, we first multiply each equation of the group (**6**), throughout, by the coefficient of b in it, and add the results; then, second, we multiply each of

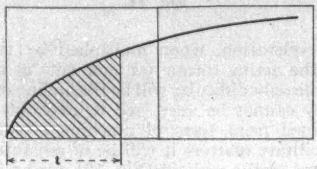


FIG. 16

the equations of the group (**6**) by the coefficient of c in it, and add the results.

Thus we have two normal equations

$$\begin{aligned} b\,(t_1^4 + t_2^4 + t_3^4 + T^4) + c\,(t_1^3 + t_2^3 + t_3^3 + T^3) \\ = B_1\,t_1^2 + B_2\,t_2^2 + B_3\,t_3^2 + B_T\,T^2 \ldots \qquad (\mathbf{7}) \\ b\,(t_1^3 + t_2^3 + t_3^3 + T^3) + c\,(t_1^2 + t_2^2 + t_3^2 + T^2) \\ = B_1\,t_1 + B_2\,t_2 + B_3\,t_3 + B_T\,T \end{aligned}$$

from which we can readily determine b and c. The equations (**7**) are so easy that no general formula will be given for their solution.

As soon as b and c are known, we need not really go to the trouble of plotting the archoid itself, unless we have any special reason for so doing; all we have to do is to introduce the constants b and c into the expression (**3**) as well as into the equations (**4**) or (**5**). This will give us what we want to know most of all, the value of the acceleration, and the points of inflection, if any.

If this article is somewhat long, it is due to the writer's earnest desire to make it easy for the practical engineer. A mathe-

matician would understand everything right from the first glance at the proposed formula (1).

The writer sincerely hopes that the archoid may be introduced into practical life, where it might clear up more than one mystery.

NOTE. *The Integral Curve.* The object of the archoid is to obviate, as much as possible, the necessity of graphical methods: the time-speed curve is plotted from actual observations, then the constants are derived from it and, finally, the acceleration is found by substituting the latter into the corresponding formula.

But, in some cases, especially where motion *in general* is considered (and not only the starting or accelerating period), it is necessary to use graphical methods, and in this connection a few words may be mentioned here regarding the integral curve, which is so useful in such investigations. In fact this

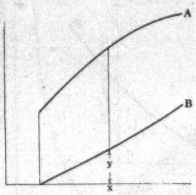


FIG. 17

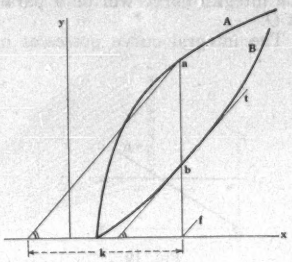


FIG. 18

curve can be used in many branches of engineering, but we shall limit ourselves to its application to the time-speed problems.

A curve B (Fig. 17), of which any ordinate y represents to some certain scale the area of another curve A, corresponding to the same abscissa x, is called the integral curve of the proposed curve A. Conversely, A is called the differential curve of B. Being given either curve we can readily construct the other curve, as will be presently explained.

It will be easily seen that, in our original problem, the archoid, or in general the time-speed curve is really the integral curve of the time-acceleration curve; on the other hand this same time-speed curve is the differential curve of the time-distance curve (we mean *distance* in general, that is, in angular sense for rotation and in lineal sense for translatory motion). So that, dynamically (not electrically), the characteristics of the motion are known just as soon as we have the time-speed curve, since both the acceleration and the space can be immediately derived from it.

The following general remarks regarding the integral curve can here be made:

1. The integral curve of any given or proposed curve can readily be constructed with a great degree of precision by means of an ordinary planimeter.

2. The inverse process of finding the differential curve of a given or proposed curve is less accurate (Fig. 18): here, for any point b of the proposed curve B we find the corresponding point a of the required differential curve A as follows: from f we lay off a suitable constant k to the left and then through l we draw a parallel to the tangent t to the proposed curve at b. The constant k is really arbitrary and is chosen so as to secure the curve A to the desired scale.

3. If the proposed curve is parallel to the axis of x, the integral curve will be a straight line through O (Fig. 19).

4. If the proposed curve is a straight line through O (Fig. 20), the integral curve will be a parabola, tangent to the axis of x at O.

The integral curve possesses many other most interesting

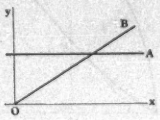


FIG. 19

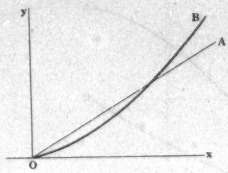


FIG. 20

properties, which will not be gone into in this communication. It is possible to design special planimeters, called *integraphs*, to draw it mechanically. It appears that Dr. Mailloux, who is a well-known expert on such matters, has even succeeded in constructing a device for the inverse problem, that is, for drawing the original curve from a given integral curve.

F. Castiglioni: I am much interested in the subject of speed-time curves. I am one of the few persons in this country who have made a specialty of this line of work. I do not refer to the kind of speed-time diagram work represented by the diagram for a so-called "average run"—which is a rather elementary piece of work—but I mean high-grade work of the kind referred to by Dr. Mailloux, speed-diagrams which take into account every change of grade, every "slowing down" in train-speed due to track-curves, crossings and bridges and other service-conditions.

I learned the methods which I use for doing this work in Germany some years ago. I did not know, at the time, their origin. It is only recently that I learned of the pioneer work

of Dr. Mailloux, and of his celebrated paper published in the A. I. E. E. PROCEEDINGS in 1902.

The matter of greatest importance in any method of plotting speed-time curves is, as Dr. Mailloux has pointed out, to determine when to stop, in going along with the speed-time curve for a given grade, so as to conform at the right time and place to the new conditions for the change of grade for the next portion of the run.

Use has been made for many years of auxiliary curves of distance-time, based upon average velocities, for determining distances, as is done in Fig. 1 of Professor Woodruff's paper.

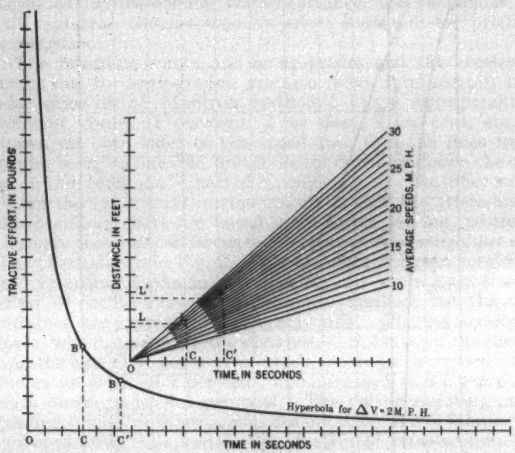


FIG. 21

The arrangement of these curves which I have used (Fig. 21) is a little different, and I think has advantages in some respects.

The method which I use, in preference to all others, for cutting off portions of speed-time curves at the proper points, involves the construction of the *speed-distance* curve. The speed-distance curve is a curve very much like a speed-time curve, and it is of interest and utility aside from its use in giving the proper distance-points for the speed-time curve. The speed-time curve is of interest to the motor manufacturer as a means of determining the power and energy consumed, but to the operating man, the speed-distance curve is really of greater interest than the speed-time curve. By the method which I use both of these curves are plotted on the same sheet.

The conditions under which we have to work in making predeterminations by means of speed-diagrams are usually more or less the same. We have the detailed profile of an existing or proposed road; we have information about the speed-requirements and regulations prescribed, the weight of the train, the number of driving motors, the required schedule-speed, and the specification of the number and length of stops. Previous experience with similar cases, or else an approximate predetermination by reference to an "average run", will tell us the motor capacity and gear-ratio, which should be chosen tentatively.

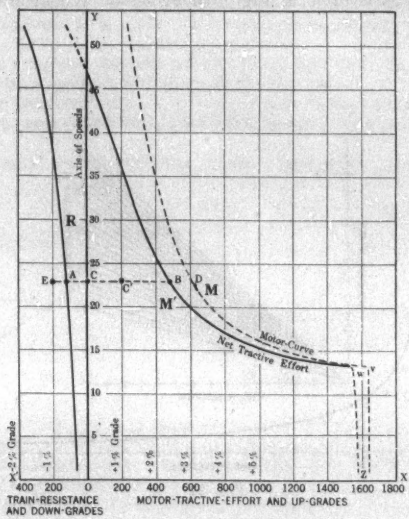


FIG. 22

We are to ascertain, by the aid of speed-diagrams, if the proposed schedule speed can be attained, and what will be the temperature and the power-consumption conditions with the motors and gear-ratio under consideration.

I will describe briefly the method of plotting speed-curves which I use. It is a German method, which I have simplified somewhat and adapted to American units.

For using this method certain curves similar to those used in the Mailloux method must be plotted on a "chart". The characteristic curve of the motor that is to be used is plotted by reference to speed and tractive effort as co-ordinates. This gives the motor-curve *M* in Fig. 22. By reference to a suitable

formula for train-resistance, a curve, R, is plotted to represent the tractive effort requisite to overcome the train-resistance for the weight of train *per motor*, (which is assumed to be 10 tons, in Fig. 22). The curve R is plotted to the left of the axis of speeds, $O\ Y$, but with the same scale of values as for the curve M. From the curves M and R a curve of *net tractive efforts*, M', is obtained by plotting the curve M anew from the curve R as a *base*, instead of the speed-axis $O\ Y$. At any given speed, the motor tractive effort, $C\ D$, measured from the curve M, will be the same as the tractive effort $A\ B$, measured from the curve M'; and as the portion $A\ C = B\ D$ represents the tractive effort expended in overcoming train-resistance, the remainder, $C\ B$, will represent the *net* tractive effort available for producing acceleration.

The retarding forces due to up-grades and the accelerating forces due to down-grades, are also taken into account by an adaptation of the Mailloux method. Lines corresponding to different grades (1 per cent, 2 per cent, 3 per cent, etc.) are drawn on both sides of the speed-axis, $O\ Y$, the lines for up-grades being on one side, and those for down-grades on the other, as in the Mailloux "Chart of Coefficients." The difference between the two charts in this respect is that the grade-lines on the Mailloux chart are based upon forces *per ton*, whereas in this case they refer to forces for the *tons of train-weight per motor*. The chart shown in Fig. 22 is used to obtain the net accelerating and retarding forces in substantially the same manner as the chart of coefficients of the Mailloux method, but the values obtained are expressed in different units. The net accelerating force, which is equal to the distance, $C\ B$, between the curve M' and the axis $O\ Y$, for a level track, becomes decreased to $C'B$ for an up-grade of 1 per cent, and increased to $B\ C + E\ C = B\ E$ on a down-grade of 1 per cent. The net accelerating and retarding forces for other grades are obtained in like manner.

For plotting the speed-curves, a strip of cross-section paper is used, of width suitable for the scales desired for speed, current, power, etc., and of length suitable for the total distance of the run or series of runs to be plotted. On this strip of paper, time and distance are both measured by horizontal distances. The distance-scale is continuous, but the time-scale starts anew at each station. The fact that the distance-scale is continuous enables all the stations, grades, curves, and the speed-regulations for crossings, bridges, etc., to be indicated at the proper points, on the sheet, before beginning to plot the speed-curves.

We first plot the portion of speed-time curve for the beginning of the run. This is an inclined straight line below the critical speed, v, Fig. 22, at which the accelerating force ceases to be constant (as represented by the dotted line $w\ z$) begins to decrease with increasing speed in the manner shown by the motor-curve M. After the straight-line portion of the speed-time curve is plotted, the corresponding portion of the speed-distance curve

is drawn. This is not a straight line, but a curved, parabolic line, the necessary points for which are obtained by a simple calculation, from the area of the initial portion of the speed-time curve (which is that of a right-angled triangle). It can be shown that the distance covered in a given time during the initial portion of the run is equal to the speed squared divided by a constant, which is proportional to the acceleration, and depends also upon the units employed for speed and distance. The co-ordinates of these parabolic curves vary with the grade. The necessary points for plotting them for a few grades are obtained by calculation; and the curves for all the grades can then be plotted on a separate sheet, from which the points required for plotting portions of these curves may then be taken, as wanted. The braking curve at the end of the run may then be drawn. It is also an inclined straight line, and, consequently, the corresponding speed-distance curve will also be of parabolic form, and the necessary points for plotting it can be determined in the same manner as for the initial portion of the run. To plot the speed-time curve between the initial and braking portions, a step-by-step process is employed, as in the Mailloux method and its modifications. Having determined upon the speed-increment which is to be used in plotting the curves (say, for instance, supposing we are taking $\triangle V = 2$ mi. per hr.), we can use the well-known hyperbola, as first employed in the Mailloux method, for finding the time-increment corresponding to the average net tractive effort obtained for that speed-increment, from the curves in Fig. 22. Fig. 21 shows the hyperbola in question. The average tractive effort, for any speed-increment, is taken off from Fig. 22, and is transferred by dividers to Fig. 21. Supposing it to be equal to BC in Fig. 22, then, in Fig. 21 the vertical distance $B\ C$ will correspond to the time interval $O\ C$. If the net tractive effort is $B\ C'$ in Fig. 22, then, in Fig. 21 the corresponding time-interval will be $O\ C'$. The time-increment thus obtained is transferred to the plotting sheet by dividers. The distance-increment is determined from the time-increment by a method which is practically the same as that mentioned in Professor Woodruff's paper, namely, by the use of a set of integral lines, each of which corresponds to an "average" velocity. These integral lines are shown in Fig. 21, for average speeds ranging from 10 to 30 mi. per hr.

The time-scale for this portion of Fig. 21 is the same as that for the hyperbola and for the plotting sheet. The distance-scale is the same as that used on the plotting sheet. The time-increment, such as $O\ C$ or $O\ C'$, is obtained by means of the hyperbola, is taken off by dividers and transferred to the plotting sheet. It is also transferred to the time-scale of the distance-diagram in Fig. 21. One point of the dividers is set on the distance-axis and the dividers are moved upward with the points in a line parallel with the time-axis until the right-hand point comes to the integral line for the proper average speed (which is 23 mi.

per hr. for the case shown in Fig. 21). When this line is reached the vertical distance from the time-axis, $L\,C = O\,L$, or $L'C' = O\,L'$, according to the case, is the required distance-increment, which is then transferred by dividers to the plotting sheet, and laid off horizontally from the last point plotted. The speed-distance curve is then plotted to this point by making the speed at that distance-point exactly the same as the speed at the corresponding time-point of the speed-time curve. The next, and all succeeding points are determined and plotted for both curves in the same manner. Thus, both the speed-time and distance-time curves are plotted simultaneously, step-by-step, the speeds going upwards for acceleration and downwards for retardations, the proper net values of tractive effort being taken, in every case, from Fig. 22, for the grade, etc., for the corresponding portion of the run; and it is the speed-distance curve which shows at what point on the line the train is, and which indicates where a given portion ends and a new portion begins. When the "run" is completed, the accuracy of plotting may be checked up by planimetry of the area of the speed-time curve. With ordinary care in the plotting, the difference between the actual and the theoretically correct curve ought to be within 3 per cent, which is satisfactory, considering the fact that the motor-curves are likely to be from 3 per cent to 5 per cent off the correct values.

The use of the speed-distance curve to supplement the speed-time curve, and to assist in its construction, is the characteristic feature of this method, distances being represented in all other methods by a distance-time curve, in which the scale of distance is vertical instead of horizontal, and therefore much more limited than in this method. The speed-distance curve, aside from its greatly facilitating and expediting the operation of cutting off and connecting the different portions of runs at the right *time* and *distance*, has the advantage of furnishing a curve similar to the speed-time curve, which gives information of interest to the operating department of the road because it shows the actual speed at every portion of the *distance*, whereas the speed-time curve only shows the speed at every instant of *time*.

I have used this method with success for extended and comprehensive studies of electric traction possibilities, in important cases like the Pennsylvania electrification at Philadelphia, the elevated and subway systems in New York, etc., where there were many different kinds of trains and schedules to be considered, for all which predeterminations had to be made. An idea of the rapidity of this method may be obtained from the sample curves which I have with me.* Two of these curves refer to 16 miles of road with 25 stations, 145 changes of grade, 50 curves, and a few speed-regulations. The actual work of plotting of these curves in pencil was done in 25 hours and 15 minutes. To do the same work by calculation methods instead of this graphical method, would have taken at least five times more time.

*Curves exhibited at meeting but not embodied here.

F. E. Wynne: The method shown in the paper is apparently a slight modification of a method described by Philip Dawson in his book, *Electric Traction on Railways*, in that the derived hyperbola and nest of straight-line curves have been superimposed upon a motor curve plotted in the usual form. While this and other graphic methods undoubtedly save considerable time where a large number of car performance curves must be plotted for varying service conditions, yet I am unable to agree with the author that his method saves time " even when one has to plot but a single speed-time curve for a particular motor load ". Considerable observation leads me to believe that the step-by-step method of calculation and plotting speed-time curves, together with the use of a planimeter which eliminates the necessity for the speed-distance curve or time-distance curve, is more rapid than any graphical method where not more than three speed-time curves have to be made for a given weight per motor.

Experience in instructing students and others has convinced me that students in particular should become thoroughly familiar with the step-by-step process before being permitted to resort to graphical processes, because by intelligently following the step-by-step method, they secure a much clearer understanding of the actual mechanics of car performance. After they have such an understanding, graphical methods are of great assistance in reducing to a minimum the labor involved in calculating a large series of performance curves.

N. W. Storer: The description of the method which Mr. Mailloux offers tonight is of the greatest interest to us all, and we shall be very much interested in seeing it amplified and written out, accompanied by the curves. It looks like a very simple and accurate method.

Mr. Castiglioni's method I can vouch for as quite reliable and accurate, as well as quick. He did considerable work in my sight some few months ago, and I can say that it was very well and quickly done. There are any number of these graphical methods, all of which are of advantage, especially to the men who have worked them out. Any man who gets used to working on one particular scheme is going to be at a disadvantage, when he attempts to work on some different method, but I think we all recognize that each of them has certain advantages.

E. E. Kimball: In the short time which remains I wish to hurry through a description of two typical railway motor characteristic curves and show how valuable the slide rule is as a handy substitute for the characteristic curves of an actual railway motor. The steps leading up to the selection of a motor to do a given service without overheating, usually require exactly similar calculations or follow the calculations of speed-time and distance-time curves, but there are some short cuts which will lead to a close approximation of the size of motors required. Furthermore, the ordinary characteristic curves giving speed, tractive effort and efficiency of a railway motor, do not contain

sufficient information regarding the resistance and core loss of the motor for one to determine the losses which have to be radiated in service or to correct a characteristic curve for a change in voltage conditions. From an analysis of these characteristic curves the writer expects to point out a procedure which he has found to be very useful in supplying this information when required.

The so-called polyphase slide rule—Fig. 23—is the same as the ordinary slide rule except that it has two additional scales; one in red between the *B* and *C* scales, which is the *C* scale inverted (reversed), and the other on the edge of the rule, which is the scale of the cubes of numbers on the *D* scale. If the ends of the scales are made to coincide as shown in Fig. 23, and values read from the *C I* and cube scales are plotted against corresponding values from the *A* scale as abscissas, the curves which result resemble the characteristic curves of a d-c. railway motor as shown by the dotted lines of Fig. 24. That is, from the "*A*"

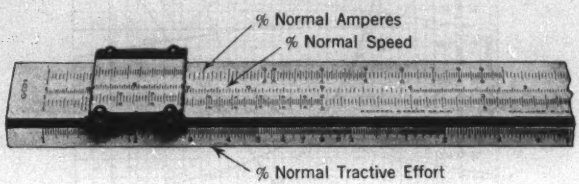


FIG. 23

scale is read per cent amperes, from the middle scale per cent speed, and from the scale on the edge of the rule per cent tractive effort. The setting of the slider in Fig. 23 gives the readings of speed and tractive effort corresponding to 160 per cent normal amperes; that is, 79 per cent speed and 203 per cent tractive effort. In Fig. 24 are shown in solid lines the characteristic curves of a composite or typical railway motor in which the values are given in percentages of the one-hour rating of the motor. If the dotted lines are accepted as representing the relation between the amperes, tractive effort, and speed for rough calculations, then it can be shown that the efficiency must be constant throughout the entire range. The equations of the dotted speed and tractive effort curves are as follows:

$$\text{Per cent speed} = \left(\frac{1}{\%\ \text{amp.}}\right)^{\frac{1}{2}}$$

and

$$\text{Per cent } T.E. = (\text{per cent amp.})^{3/2}$$

The writer has made no attempt to derive an equation which will represent the characteristics of a railway motor closer than the ones just given, for the reason that the chief value of these equations lies in the fact that it is easy to remember to read per cent amperes on the A scale, per cent speed on the middle scale and per cent tractive effort on the cube scale.

For speed-time and distance-time curves one is not so much interested in the relation between speed and amperes or tractive

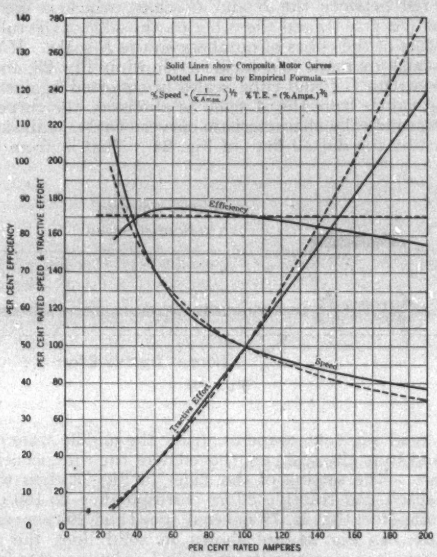


FIG. 24

effort and amperes as he is in the relation between speed and tractive effort.

From the above equations it follows that per cent speed $= \left(\frac{1}{\%\,T.E.}\right)^{1/3}$ or in other words: *The speed of a d-c. railway motor is approximately inversely proportional to the cube root of the tractive effort.*

The dotted speed curve in Fig. 25 is plotted with tractive effort instead of amperes as the variable, that is, the two tractive

effort curves of Fig. 24 have been made to coincide and the speed curve modified so as to maintain the same relation between speed and tractive effort as exists in Fig. 24. The closeness with which the dotted and solid speed curves of Fig. 25 agree shows the relation between speed and tractive effort for the typical railway motor is closely represented by the rule just stated.

The value of this relation in determining the capacity of railway motors for a given service is best illustrated by an example.

Assume a 50-ton car to be geared for a maximum speed of 60 mi. per hr., a train resistance value of 25 lb. per ton at 60 mi. per

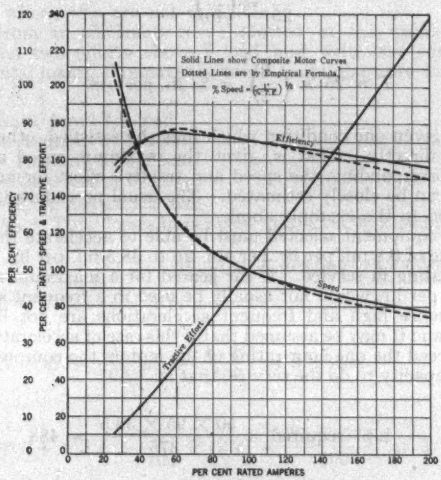


FIG. 25

hr. and a rate of acceleration of 0.8 mi. per hr. per sec.; to determine the h.p. capacity of motors required.

At 60 mi. per hr. the tractive effort delivered by the motors just balances the train resistance, *i. e.*, 25 lb. per ton. The final speed reached on the control during the period of notching up (beginning of motor curve acceleration) is unknown, but we know what the tractive effort must be to give 0.8 mi. per hr. per sec. acceleration during the control period. It is 80 + 15 = 95 lb. per ton if we assume it takes 100 lb. per ton to produce 1 mi. per hr. per sec. and if the train resistance at this lower speed is taken at 15 lb. per ton.

By the rule just stated $\frac{V}{60} = \left(\frac{25}{95}\right)^{1/3}$

$$\text{or } V = 60 \times \left(\frac{25}{95}\right)^{1/3} = 60\,(0.263)^{1/3} = 38.5 \text{ mi. per hr.}$$

Likewise for any other speed the tractive effort can be obtained: that is, at 40 mi. per hr.

$$\frac{T}{25} = \left(\frac{60}{40}\right)^3$$

or

$$T = 25 \times \left(\frac{3}{2}\right)^3 = 84 \text{ lb. per ton.}$$

Thus, given one condition which must be satisfied, other points follow directly. That is, given the maximum speed and friction corresponding, the speed and tractive effort for any other point can be closely estimated. The usual procedure is as just outlined in the example above.

The equipment selected must be able to accelerate the car at the rate of 0.8 mi. per hr. per sec. up to 38.5 mi. per hr. without overheating in service. A car geared for a maximum speed of 60 mi. per hr. would not usually be used in a frequent stop service, hence high and frequent accelerations are not likely to occur, and it may be assumed that if this rate of acceleration does not exceed the one-hour rating of the motors the equipment will have capacity to do the service, that is:

$$\text{h.p. required} = \frac{50 \times 95 \times 38.5}{375} = 488$$

let us say four 125-h.p. motors.

One would look for characteristic curves of 125 h.p. motors and select a gearing which would give sufficient tractive effort at 60 mi. per hr. to balance the friction.

For lighter and slower speed cars which are generally used in frequent stop service a rate of acceleration of 0.8 mi. per hr. per sec. is not sufficient either for performing the usual schedules nor does it leave enough margin for radiating the losses in service. It is usual to select an equipment for these services which will produce an acceleration of 1.00 to 1.50 mi. per hr. per sec. at the one-hour rating of the motors. This is on the basis of non-ventilated motors.

Ventilated motors radiate losses much faster than the non-ventilated pole type, hence the h.p. rating of motors, if venti-

lated motors are proposed, will be less than found by the above method. As a first approximation, 80 per cent of the values found above will lead to some definite design of motors for which the radiating constants are known. From these it can be determined what the probable heating will be in service.

To segregate the losses of a railway motor and thereby determine its resistance, the writer has found that the core loss may be represented by the equation $CL = K I^{1/3}$, where K is a constant and I represents current.

The Standardization Rules of the A. I. E. E. (Appendix I of Rules) suggest that the gear and friction losses be taken at five per cent for all loads above $\frac{3}{4}$ load for approximate determinations when tests are not available.

Then from an efficiency curve plotted in this fashion we may select two points above $\frac{3}{4}$ load and write the equation for the total losses, eliminate the terms containing core loss and solve for R.

Thus for 3/4 and 3/2 load

if I = Amperes at 3/4 load

$2\,I$ = Amperes at 3/2 load

L = Core loss at 3/4 load

$\sqrt[3]{2}\,(L)$ = Core loss at 3/2 load

K_1 and K_2 = Total losses in per cent at 3/4 and 3/2 load respectively.

= 100 − per cent efficiency at 3/4 and 3/2 load respectively.

E = Rated voltage of motor or voltage marked on curve.

$$\text{Then } I^2R + L + \frac{5}{100}\,EI = \frac{K_1 EI}{100} \text{ at 3/4 load} \qquad (1)$$

$$\text{And } (2I)^2 R + \sqrt[3]{2}\,L + \frac{5}{100}\,E\,(2\,I) = \frac{K_2\,E\,(2I)}{100} \text{ at 3/2 load} \qquad (2)$$

Or eliminating L and substituting 1.26 for $\sqrt[3]{2}$

$$2.74\,I^2R + \frac{3.7\,E\,I}{100} = \frac{(2K_2 - 1.26\,K_1)}{100}\,EI$$

$$R = \frac{(2K_2 - 1.26\,K_1 - 3.7)\,E}{2.74 \times 100 \times I}$$

$$\text{Simplified, } R = \frac{(8\,K_2 - 5\,K_1 - 15)\,E}{1100\quad I} \text{ approximately}$$

From the derivation of this formula it follows that care must be taken to select two points both of which are above 3/4 load, and the loads must bear the relation 2 to 1. That is, if one point is taken at 7/8 load the other must be taken at 7/4 load, etc. I is the current corresponding to the lesser of the two points chosen.

Example. Find the per cent copper and core loss represented by the typical characteristics shown in Fig. 24 or 25.

These curves are shown over a sufficient range to obtain three determinations of the resistance. For check readings, we will take the losses in pairs as follows:

$K_{80}, K_{160}; K_{90}, K_{180}; K_{100}, K_{200}$

$K_{80} = 100 - 86.5 = 13.5; K_{90} = 14; K_{100} = 14.5;$

$K_{160} = 100 - 82.0 = 18.0; K_{180} = 20.5; K_{200} = 22.0$

$$R = \frac{(8 \times 18 - 5 \times 13.5 - 15)\,E}{1100 \times 80} = 0.0007\,E$$

$$R = \frac{(8 \times 20.5 - 5 \times 14 - 15)\,E}{1100 \times 90} = 0.0008\,E$$

$$R = \frac{(8 \times 22.0 - 5 \times 14.5 - 15)\,E}{1100 \times 100} = 0.000805\,E$$

Ave. $R = 0.00077\,E$

$$\text{Per cent } I^2R \text{ (1-hr rating)} = \frac{I^2R \times 100}{E \times I} = 100 \times 0.00077 \times 100$$

$$= 7.7 \text{ per cent}$$

Per cent CL (1-hr. rating) $= 14.5 - (5 + 7.7) = 1.8$ per cent.

The accuracy of this determination of the resistance of a motor depends upon how accurately the efficiency can be read. A single determination may be 25 per cent out because of accumulated errors in reading the efficiencies, but usually the error is less than 10 per cent.

E. C. Woodruff: With regard to the accuracy of a graphic method—when the data are given in the form of a curve and the object of the calculation is to obtain another curve, graphic methods used for the intermediate steps will not reduce the accuracy of the calculation. Any analytical steps used will involve a double translation from curves to tabulated data and vice versa, and will give even more chances for errors in said translations.

C. O. Mailloux (communicated after adjournment): A comparison of the chart used in the method of Mr. Cas-

tiglioni (Fig. 22) with that shown in Fig. 9 of my 1902 paper, indicates clearly the identity of the principle of the two methods. Curves M, M' and R in Mr. Castiglioni's chart are the same as curves M, N and R' (and also R) in my paper. They seem, at first, to be different because the axes of co-ordinates are disposed differently and the scale of tractive efforts is also different. In my chart, speeds are plotted as abscissas and tractive efforts as ordinates, because this puts the independent variable, speed, in the proper cartesian position and relation with respect to the "function," *i.e.*, the tractive effort. In Mr. Castiglioni's chart these relations are transposed, which makes, apparently, the speed a function of the tractive effort, something not physically possible. The arrangement is not logical, and I fail to see that it has any advantages whatever to excuse it. In regard to tractive effort scales, there are two differences. First, I deal, in Fig. 9, with all accelerating and retarding forces on the basis of their action on *one ton* of train-weight, whereas, in Mr. Castiglioni's chart, these forces are dealt with on the basis of the action produced *per motor*. The advantage of this change appears very doubtful. Second, in Fig. 9 of my paper, the curve R represents the actual train-resistance per ton, same as the formula by reference to which the curve was plotted. The lines parallel with the speed-axis which correspond to up-grades and down-grades also represent forces per ton. The great advantage of this plan is that the curves R and Q and the grade-lines in my chart are definite and require no change with the train-load per motor. In Mr. Castiglioni's Fig. 22, the curve R and the grade-lines have to be changed every time the train-weight per motor changes. In my chart, a change in motor-load requires only the curves M and N to be changed. In reality, the curve N does not have to be changed, because by drawing the curve R both above and below the axis of speeds, as is done in Fig. 9, the net values of tractive effort are obtained by the difference in ordinates between curves M and R. As pointed out in my discussion, several curves of tractive effort M corresponding to different motors and loads, can be put on the same chart. In regard to the measurement of tractive effort, I still prefer to translate tractive effort directly into acceleration-values, and to use a scale of *accelerations* as is done in Fig. 9, because the acceleration-values indicated by such a scale convey a definite idea of what is actually happening and tell us something we want to know, namely, how rapidly the train is *gaining* or *losing* speed, at any moment. Tractive effort and acceleration bear to each other the relation of *cause* and *effect*. The first represents the *agency*, the second the *result* produced by it. In this case we have to measure and express a *result*, not a *cause*, and it is wrong to express the result in terms of the cause. A scale of acceleration-coefficients such as used in Fig. 9 of my paper expresses the *result* produced, *directly* and in the *correct unit*, the mile per hour per second, (or the kilometer per hour per second),

which unit is now recognized and adopted internationally since the Turin Electrical Congress in 1911. The thought of even trying to express acceleration in terms of pounds of tractive effort per second per second is supremely ridiculous. The use of a scale of tractive effort in place of a scale of accelerations has no practical advantages and it is open to the objection of being both illogical and inconsistent. A scale of tractive efforts may be used, if desired, to *supplement* the scale of accelerations, but it should never be used to *replace* it. In Fig. 9 of my paper, the scale of acceleration may be converted into a scale of tractive efforts per ton by multiplying the acceleration values by the constant 91.2. In some cases, a scale of tractive efforts has been added to the chart; but the use of this scale for the purposes for which the acceleration scale is manifestly the proper scale has not been encouraged; and when once students become familiar with the theoretical principles involved, they see the logic and propriety of the units and scales used and prefer them to all others; and the scale of tractive efforts loses all interest and utility.

The instances of rapid work done by Mr. Castiglioni by his method are very interesting as evidence of the merits of graphical methods. I confess that I am still a bit skeptical on the point of accuracy, because the possibilities of error noted in connection with Prof. Woodruff's method do not appear to be wholly eliminated. The use which is made of the speed-distance curve is ingenious, but the method by which the distance increments are obtained, being based upon straight-line integrations corresponding to average velocities, as in Prof. Woodruff's method, appears to be open to the same objections and the same liability to cumulative errors. As pointed out and as shown by the comparison given in Fig. 4 of my discussion, this method of obtaining distance and time increments is at best much more laborious and far less accurate than the method based upon the use of the distance-time integral, as obtained by the integraph. When the speed-distance curve is desired, as a supplement to the speed-time curve, it can be readily and quickly plotted from the distance-time curve obtained by the integraph.

The chart method described in my 1902 paper is capable of doing work at least as rapidly; and, of course, from the point of view of accuracy, not only in plotting the speed-time curve, but also and more especially the "subsidiary" curves, which, as shown in my paper, are the ones of greatest interest and importance, the chart method described in my 1902 paper, when used with the integraph, can fearlessly challenge and meet all methods that have come to light thus far.

D. D. Ewing (communicated after adjournment): In the first paragraph of his paper, Prof. Woodruff makes the statement, "Students that have struggled with the usual step-by-step process* * * * seem to acquire a new interest in the subject when this method is proposed." I wonder if this "new

interest" is not, partly at least, the more or less fictitious sort of interest which students display whenever a short-cut method of any kind is proposed. In other words, it may be that they are more interested in finding a method of lessening their labor than they are in the theory of the thing they are studying.

Viewing the method from the standpoint of a teacher of engineering there are the following objections to it: 1. It does not give the student the drill on the underlying theory of the curves that the step-by-step method does. The writer does not wish to be understood as decrying the use by students of graphical methods of solving problems. Such methods are extremely valuable whenever they enable the student to get a clearer conception of the problem. However, this type of graphical method belongs to what might be termed the "slide rule" class, and just as any person of ordinary intelligence can be taught to solve more or less difficult problems, rapidly, with the slide rule, without understanding the theory underlying the problem, so can a person be taught to use this type of graphical method. Such methods tend to become mechanical, thereby facilitating the solution of problems. We are not so particular about the student's "speed" as we are about his understanding. The step-by-step method which brings in the elementary theory underlying the construction of the curve in the calculations for each point gives the student a much firmer grasp on the theory than could any graphical method. 2. The large number of curves on the sheet tends to confuse the student. This objection is so obvious that it does not need discussion.

Viewed from the standpoint of the practising engineer, the method presents some valuable features. It is compact even if it is somewhat complicated. Where a large number of similar speed-time curves is to be calculated, the method would probably effect a considerable saving in time besides eliminating to a large degree the mental strain that always accompanies analytical methods of solving problems.

In the last sentence the statement is made that " the method saves time and trouble when one has to plot but a single speed-time curve for a particular motor load." The truth of this statement is not obvious. While the writer has not given this particular method a thorough tryout, his past experience leads him to believe that unless a large number of speed-time curves is to be calculated, the step-by-step method is the shortest, provided care is taken to systematize the work. All time saved by the graphical method must be saved while calculating that part of the acceleration line of the curve which covers the time during which the motors are accelerating with line voltage across their terminals. Where the runs are short, but few points on this part of the curve are needed and therefore there is little opportunity to shorten the time required for the calculation of the entire curve.

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EFFECT OF ALTITUDE ON THE SPARK-OVER VOLTAGES OF BUSHINGS, LEADS AND INSULATORS

BY F. W. PEEK, JR.

ABSTRACT OF PAPER

The dielectric strength of air decreases with decreasing pressure and increasing temperature; that is, with the density. Therefore, at high altitudes where the barometric pressure is low, brush discharge starts and spark-over takes place at lower voltages than at sea level. The effect of air density on corona, and spark-over between spheres, etc., has already been given.

In the following investigation the effect of altitude and temperature on the surface spark-over of leads and insulators was studied by placing them in a large wooden cask and gradually exhausting the air. Correction factors are given for various standard types. The spark-over voltage decreases almost directly with the air density.

The following gives an idea of the magnitude of the correction:

The spark-over voltage of a certain string of insulators at 25 deg. cent. is

Kv.	Altitude	Possible Location
300	0	Sea level
250	5,000 ft.	Denver
205	10,000 ft.	Colorado

THE following investigation was made to determine the effect of air density, and therefore of altitude or barometric pressure, and temperature, upon the spark-over voltages of leads, insulators, etc.

The dielectric strength of air decreases with decreasing pressure and increasing temperature; that is, with the relative density or with the average spacing of the molecules. If the relative density is taken as unity at a standard pressure of 76 cm. and a temperature of 25 deg. cent., the relative density at any other pressure and temperature is

$$\delta = \frac{3.92\,b}{273 + t}$$

where b = barometric pressure in cm.
and t = temperature in degrees cent.

For the uniform field between parallel planes the spark-over voltage decreases directly with δ. If e is the spark-over voltage for a given spacing at $\delta = 1$, the spark-over voltage e_1 at $\delta = 0.5$ is

$$e_1 = 0.5\,e$$

The effect is the same for the same value of δ whether δ is changed by temperature or by pressure. This has been shown elsewhere.* For non-uniform fields, as those around wires, spheres, insulators, etc., the spark-over voltage decreases at a lesser rate than the air density. The theoretical reasons for this have been given, as well as the laws for regular symmetrical electrodes, for cylinders, and spheres.†

It is, however, not possible to give an exact law covering all types of leads, insulators, etc., as every part of the surface has its effect. The following curves and tables give the actual test results on leads, insulators, and bushings of the standard types. The correction factor for any other lead or insulator of the same type may be estimated with sufficient accuracy. When there is doubt, δ may be taken as the maximum correction. It will generally be advisable to take δ because the local corona point on leads and insulators will vary directly with δ. This is so because the corona must always start on an insulator in a field which is locally more or less uniform.

The tests were made by placing the leads or insulators in a large wooden cask 2.1 meters high by 1.8 meters inside diameter, exhausting the air to approximately $\delta = 0.5$, gradually admitting air and taking the spark-over voltage at various densities as the air pressure increased. The temperature was always read, and varied between 16 and 25 deg. cent. The cask is shown in Fig. 1.

At the start a number of tests were made to see if a spark-over in the cask had any effect upon the following spark-overs by ionization or otherwise. It was found that a number of spark-overs could be made in the cask with no appreciable effect. During the test, the air was always dried and the surfaces of the insulators were kept clean.‡

Table I is a typical data sheet. Tables II to VI give even values of δ and the corresponding measured correction factors. If the spark-over voltage is known at sea level or $\delta = 1$ (76 cm. bar., temperature 25 deg. cent.), the spark-over at any other value of δ may be found by multiplying by the corresponding correction factor. It will be noted that in most cases the correction factors are very nearly equal to δ.

Law of Corona II, A. I. E. E. TRANS., 1912, p. 1051.

†*Law of Corona II*, A. I. E. E. TRANS., 1912, p. 1051, and *Law of Corona III*, A. I. E. E. TRANS., 1913, p. 1767.

‡In these tests, corrections have been made for wave shape, etc., and the voltages checked by *sphere gap*. Voltages measured by needle gap are incorrect and indicate higher voltages than really exist.

[PEEK]

FIG. 1—CASK FOR STUDY OF VARIATION OF SPARK-OVER AND CORONA VOLTAGE WITH AIR DENSITY OR ALTITUDE

TABLE I

SUSPENSION INSULATOR

Bar. cm.	Vac. cm.	Pressure cm.	Temp. cent.	δ	Kilovolts arc-over
75.4	37.4	38.0	22.	0.50	121.0
"	34.3	41.1	"	0.54	131.0
"	30.0	45.4	"	C.60	144.0
"	26.4	49.0	"	0.65	158.5
"	23.0	52.4	"	0.70	165.0
"	19.3	56.	"	0.74	177.5
"	17.5	57.9	"	0.77	183.2
"	15.0	60.4	"	0.80	195.0

TABLE II

LEADS. (See Fig. 17)

δ	Correction Factor for Lead Shown in			
	Fig. 2	Fig. 3	Fig. 4	Fig. 5
1.00	1.00	1.00	1.00	1.00
0.90	0.92	0.91	0.92	0.92
0.80	0.83	0.82	0.83	0.85
0.70	0.74	0.72	0.75	0.77
0.60	0.70	0.65	0.64	0.66
0.50	0.61	0.56	0.54	0.57

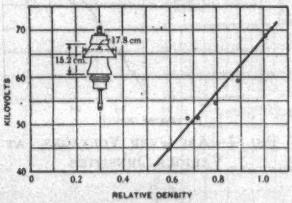


FIG. 2—ARC-OVER VOLTAGES AT VARIOUS DENSITIES

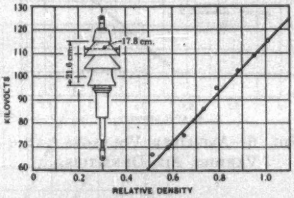


FIG. 3—ARC-OVER VOLTAGES AT VARIOUS AIR DENSITIES

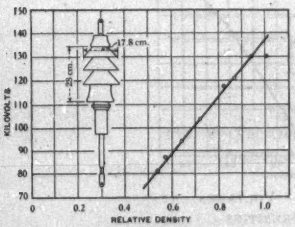


FIG. 4—ARC-OVER VOLTAGES AT VARIOUS DENSITIES

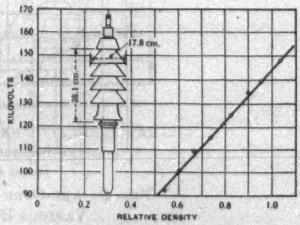


FIG. 5—ARC-OVER VOLTAGES AT VARIOUS DENSITIES

TABLE III

POST AND PIN INSULATORS. (See Fig. 20)

δ	Correction Factor for Insulator Shown in		
	Fig. 6	Fig. 7	Fig. 8
	Post	Pin	
1.00	1.00	1.00	1.00
1.90	0.93	0.91	0.94
0.80	0.84	0.81	0.86
0.70	0.76	0.73	0.75
0.60	0.68	0.62	0.65
0.50	0.60	0.52	0.53

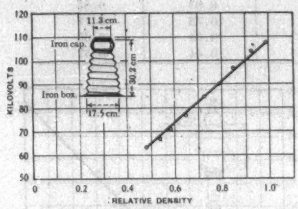


FIG. 6—ARC-OVER VOLTAGES AT VARIOUS AIR DENSITIES.

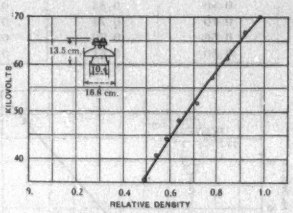


FIG. 7—ARC-OVER VOLTAGES AT VARIOUS DENSITIES

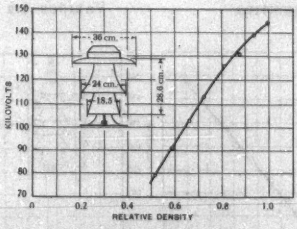


FIG. 8—ARC-OVER VOLTAGES AT VARIOUS DENSITIES

TABLE IV

SUSPENSION INSULATOR FIG. 9. (See Figs. 18 and 19)

δ	Correction Factor for Units in String as follows				
	Number of Units				
	1	2	3	4	5
1.00	1.00	1.00	1.00	....	....
0.90	0.96	0.93	0.90	....	....
0.80	0.91	0.84	0.80	....	....
0.70	0.86	0.76	0.70	....	....
0.60	0.80	0.66	0.60	....	....
0.50	0.72	0.55	0.50	....	....

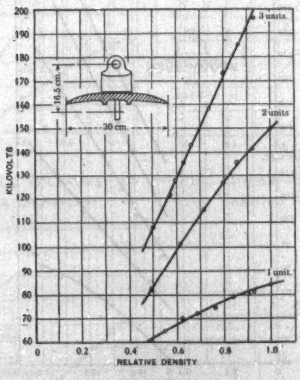


FIG. 9—ARC-OVER VOLTAGES AT VARIOUS AIR DENSITIES

TABLE V

SUSPENSION INSULATOR, FIG. 10. (See Figs. 18 and 19)

δ	Correction Factor for Units in String as follows				
	Number of Units				
	1	2	3	4	5
1.00	1.00	1.00	1.00	1.00	1.00
0.90	0.95	0.91	0.90	0.90	0.91
0.80	0.89	0.81	0.81	0.81	0.82
0.70	0.80	0.72	0.72	0.72	0.73
0.60	0.70	0.63	0.63	0.63	0.65
0.50	0.57	0.53	0.53	0.53	0.57

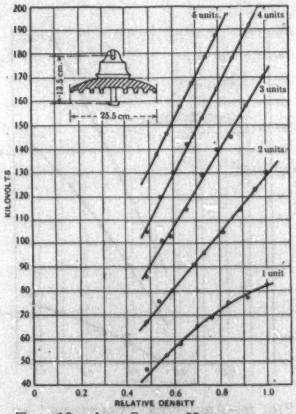


FIG. 10—ARC-OVER VOLTAGES AT VARIOUS AIR DENSITIES

TABLE VI
SUSPENSION INSULATOR, FIG. 11. (See Figs. 18 and 19)

δ	Correction Factor for Units in String as follows — Number of Units				
	1	2	3	4	5
1.00	1.00	1.00	1.00	1.00	....
0.90	0.94	0.92	0.90	0.90	....
0.80	0.87	0.84	0.80	0.80	....
0.70	0.81	0.73	0.70	0.70	....
0.60	0.72	0.63	0.60	0.60	....
0.50	0.62	0.52	0.50	0.50	....

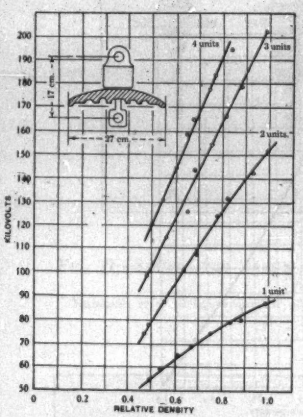


FIG. 11—ARC-OVER VOLTAGES AT VARIOUS AIR DENSITIES

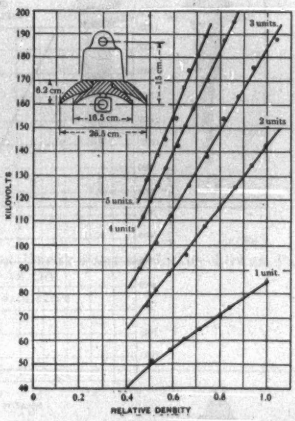


FIG. 12—ARC-OVER VOLTAGES AT VARIOUS AIR DENSITIES

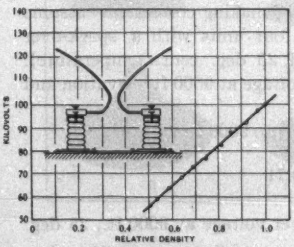


FIG. 13—ARC-OVER VOLTAGES AT VARIOUS AIR DENSITIES
Horn gap spark-over. Gap spacing 14 cm. Diameter of horns 1.27 cm.

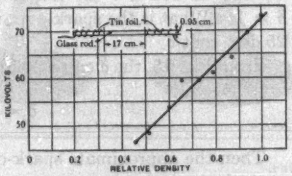


FIG. 14—ARC-OVER VOLTAGES AT VARIOUS AIR DENSITIES

Fig. 15 is a curve giving different altitudes and corresponding δ at 25 deg. cent. If the spark-over voltage is known at sea level at 25 deg. cent., the spark-over voltage at any other altitude may be e timated by multiplying by the corresponding δ, or more closely, if the design is the same as any in the tables, by the correction factor corresponding to δ. If the local corona starting point is known at sea level, it may be found for any altitude by multiplying by the corresponding δ. The barometric pressure corresponding to different altitudes is given in Fig. 16. Figs. 17 to 20 show the insulators used in these tests.

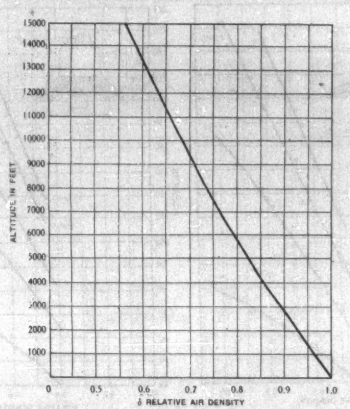


FIG. 15

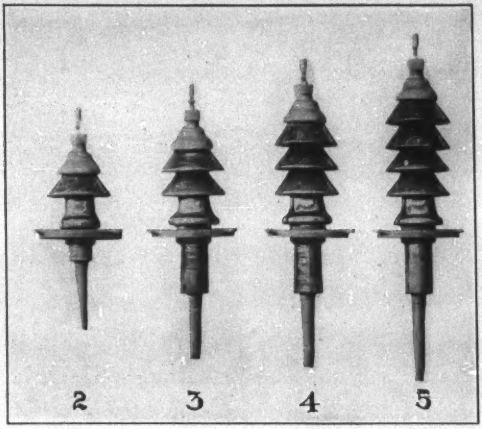
As an example of the methods of making corrections: assume a suspension insulator string of four units with a spark-over voltage of 205 kv. (at sea level, 25 deg. cent. temperature). $\delta = 1$. What is the spark-over voltage at 9000 ft. elevation and 25 deg. cent.?

From Fig. 15, the δ corresponding to 9000 ft. is

$$\delta = 0.71$$

Then the approximate spark-over voltage at 9000 ft., 25 deg. cent., is

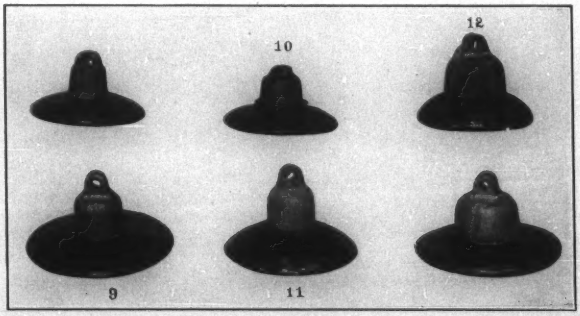
$$e_1 = 0.71 \times 205 = 145 \text{ kv.}$$



[PEEK]

FIG. 17—SPARK-OVER TAKEN ON UPPER PART OF LEAD—LOWER PART IN OIL

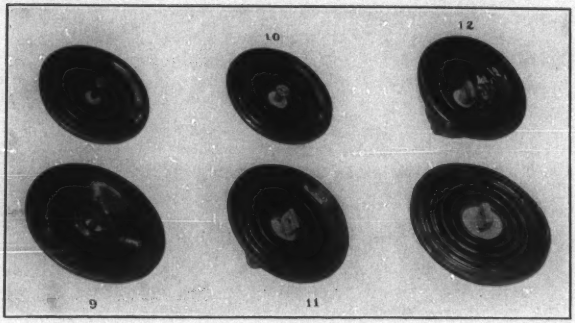
Numerals refer to figure number of data curve.



[PEEK]

FIG. 18—TYPES OF PORCELAIN INSULATORS TESTED AT VARIOUS AIR DENSITIES

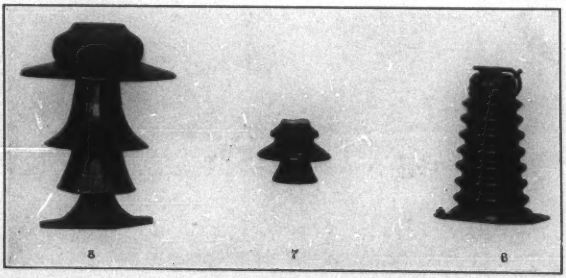
Numerals refer to figure number of data curve.



[PEEK]

FIG. 19—TYPES OF PORCELAIN INSULATORS TESTED AT VARIOUS AIR DENSITIES

Numerals refer to figure number of data curve.



[PEEK]

FIG. 20—TYPES OF PORCELAIN INSULATORS TESTED AT VARIOUS AIR DENSITIES

Numerals refer to figure number of data curve.

If this happens to be the insulator of Fig. 10, the correction factor corresponding to $\delta = 0.71$ is found in Table V, by interpolation, to be 0.73. The actual spark-over voltage for this special case is

$$e_1 = 0.73 \times 205 = 150 \text{ kv.}$$

The first estimate is on the safe side and close enough for all practical purposes. Thus, for practical work the correction may generally be made directly by use of Fig. 15.

The spark-over voltage of an insulator is 100 kv. at 70 cm.

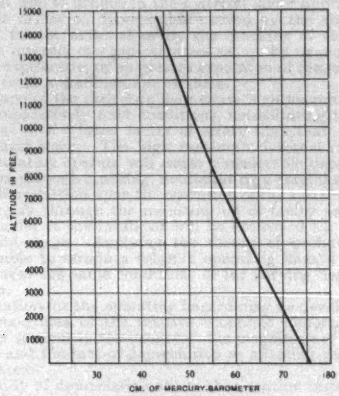


FIG. 16

barometer and 20 deg. cent. What is the approximate spark-over voltage at 50 cm. barometer and 10 deg. cent.?

$$\delta_1 = \frac{3.92 \times 70}{273 + 20} = 0.94$$

$$\delta_2 = \frac{3.92 \times 50}{273 + 10} = 0.61$$

$$e_1 = 100 \times \frac{0.61}{0.94} = 65 \text{ kv.}$$

If the local corona starting point is known at, say, sea level, it may be found very closely for any other altitude by multiplying by the correction δ.

The spark-over voltage of insulators will vary somewhat from day to day, due to humidity. There is also some variation for different units. The humidity voltage variation on the insulator is possibly as high as 7 per cent, from day to day. Comparative tests of different types, when desired, should be made at the same time. The humidity correction, on the insulator itself, is too complicated to make and of no practical value. Care must be taken, however, to use a measuring gap unaffected by humidity; that is, a sphere gap.

Presented at the 302d Meeting of the American Institute of Electrical Engineers, New York, December 11, 1914.

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INSULATOR DEPRECIATION AND EFFECT ON OPERATION

BY A. O. AUSTIN

Abstract of Paper

Investigation shows that insulator trouble increasing with time is not due to fatigue in the material under applied working loads, but rather to depreciation caused by the absorption of water by porous material or by the cracking of the dielectric from high internal mechanical stress set up by uneven temperature in the dielectric, or by greater expansion of cement or metal, or stress from a combination of these.

The shape of the dielectric may cause high maximum stresses under comparatively mild conditions, necessitating the working of material with a lower factor of safety than that permissible even in steel work. The high maximum internal stress under which insulators operate will cause considerable depreciation in some types through cracking, necessitating a careful study of the effect of depreciation upon the operation of the system. Trouble comes largely through the matching up of faulty parts so that the remainder of the insulator will be destroyed by a comparatively mild surge. Applying the theory of probability, it is then possible to obtain a relative operating hazard for the insulator under the same conditions or for varying degrees of depreciation.

An equation for the operating hazard may be developed which gives a good idea of the relative economic importance of the number of sections in the insulator, the magnitude of the switching surge and the rate of depreciation as affecting the reliability of the system.

The study of depreciation shows that routine tests which will tend to eliminate future depreciation, or refinements in the mechanical features of the insulator, are of far more importance in producing reliability than the designing of insulators to withstand extremely severe dielectric design tests, for insulators which may have extremely high dielectric strength will cause trouble through cracking from internal stress.

THE growing investments dependent upon the transmission line make the study of factors governing reliability in the insulator of ever-increasing economic importance. In view of this, it is hoped that this article will throw some light on insulator failures and be of assistance in deciding on the refinements and size of insulator necessary for a given system.

Even with more severe conditions placed on the insulator, recent lines have continued to make a much better showing. Some systems have had no insulator failures, while others have

operated for a period of several years only to run into increasing trouble, in some instances necessitating the entire reinsulating of the line.

Where insulator trouble increases with time, it is only natural to attribute the trouble to fatigue in the insulator. Upon looking into the subject, however, it is evident that this is not necessarily the case, for the failures may be due to a number of entirely different causes.

Suspension insulators give the best available data, although failures of pin type insulators have been far more numerous, in some instances a visual inspection showing cracks developed in over 60 per cent of the insulators.

A few pin type insulators which have cracked after several years' service are shown in Fig. 1. An examination of this class of failure shows that there must be a strong radial force which splits the outer parts or shears the head of the cylinder from the side wall. This force can come from several sources, but as the porcelain does not seem to be appreciably affected either mechanically or electrically outside of the cracks it would appear that the breakdown is due more to a rather high stress, than to a low stress acting for a long time.

It is quite likely that the stress set up is that due to uneven expansion from varying temperature and from an expansion of the cement.

Porcelain, like most dielectrics, is a very poor conductor of heat, so if the insulator has become hot in the sun or from surface leakage, and is then suddenly cooled by rain, there will be a considerable difference in temperature between the outer and inner parts. This difference in temperature may set up an average tensile stress of several hundred pounds in the outer members.

This average stress is hardly high enough to cause any damage, but the shape of the dielectric may be such that a very high maximum stress is set up, causing a crack, as along AB in Fig. 2.

There is no doubt that the defect comes from internal stress, but as this stress may be set up by uneven temperature and expansion in the dielectric or by cement expansion, it is not easy to determine the cause.

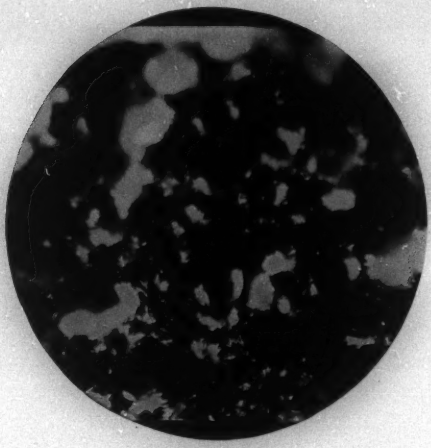
Tests on the insulators show that there may be considerable difference in temperature between inner and outer surfaces which may account for destructive stresses in some instances, but hardly accounts for failures in other cases, particularly where insulators have been known to crack in storerooms and in protected places where there has been no sudden change of temperature.

[AUSTIN]

FIG. 1

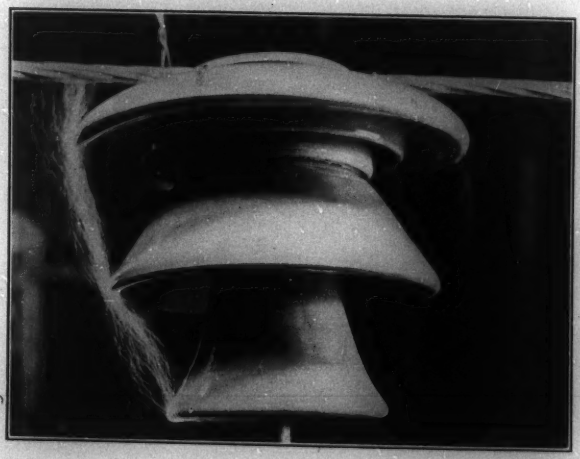
[AUSTIN]

FIG. 4



[AUSTIN]

FIG. 5



[AUSTIN]

FIG. 6

It is also significant that trouble usually develops at railway crossings first. While it is possible that the insulators may become hotter, owing to the black surface or increased leakage, it appears that the sulphur fumes in the smoke attack the cement and increase the crystalline growth, presumably of calcium sulphate. This crystallization causes expansion, setting up a stress which, combined with that due to difference in temperature, may produce exceedingly high strains.

It is not surprising that there should be some trouble from cement expansion, for in general, little attention has been given

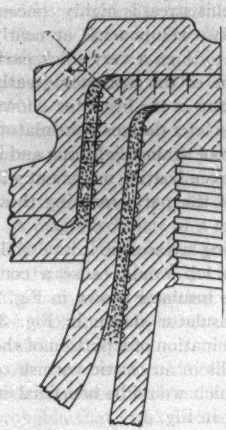


FIG. 2

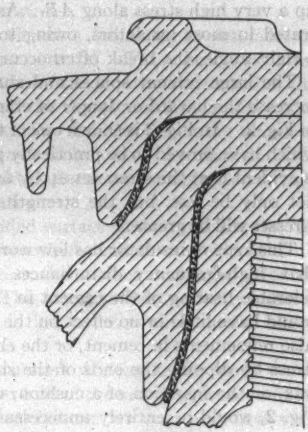


FIG. 3

to this rather difficult subject, and even where there has been, it is difficult to predict expansion from the formation of acids by static discharge in the cement or effect of continued weathering.

Owing to deficiency in mechanical strength, European porcelain does not seem to withstand the mechanical stress very satisfactorily, and it has been general practise abroad to avoid cementing, or to use special cements at greatly increased cost.

A microscopic examination of the cement sometimes shows a marked crystalline growth in the cement, particularly where the insulators are near railroad crossings, or in cement exposed to continued weathering.

Fig. 4 is reproduced from a photomicrograph of cement taken from the insulator on the right of Fig. 1. Taken at a magnification of 49 diameters, a few crystal growths are visible. Fig. 5 shows a marked growth in the cement from a strain insulator. These insulators gave trouble in a little over a year, so it is evident that cement expansion played an important part in causing failure.

Fig. 2 shows a section of an ordinary pin-type insulator which usually cracks along the line AB. It is readily seen that a contraction of the outer part or expansion from the cement will set up a very high stress along AB. As this stress is highly concentrated in most insulators, owing to two components at nearly a right angle, the break often occurs through a very thick part.

The large cement spaces and shape of the insulator greatly increase the hazard or danger of cracking in the insulator shown in Fig. 2. In Fig. 3 is shown one of the later designs of insulators which have proved to be practically proof against lightning and it is evident that the stress set up by uneven heating or cement will not only be less, but the strength of the parts resisting these stresses will be greater.

This type of insulator has low working stresses, so it is possible that high-frequency disturbances which would cause a considerable heating of the cement in the insulator shown in Fig. 2 would have little or no effect on the insulator shown in Fig. 3. Also refinements in cement, or the elimination of a portion of the stress by dipping the ends of the shells in an elastic varnish or wax, or the insertion of a cushion, which would be beneficial in Fig. 2, would be entirely unnecessary in Fig. 3.

The material is so distributed in the later types of insulators that not only are exceedingly high tests obtained on the parts, but a small protecting air path is provided between conductor and pin to act as a safety valve for surges.

Fig. 6 shows an improved insulator, a section of which is shown in Fig. 3, flashing over at 216 kv. for a striking distance of 14 in. (35.5 cm.), and having a total part test of over 300 kv.

There is nothing in practise to show that anything would be gained by increasing the conductivity of the cement in insulators of this type or metallizing the surfaces to reduce heating from flow of charging current under high-frequency surges, although tests on the oscillatory transformer may show that this is beneficial in the ordinary insulator with its high charging current.

Fig. 7 shows typical breaks in two different suspension insulators. On the left is shown a disk with crack in the groove at the shoulder from combined expansion of the cap and cement exposed to weathering. The stress is concentrated by the shape of the insulator and the cement groove. This groove affects the strength somewhat like a scratch in a pane of glass. Insulators may also be cracked slightly at this point by too high mechanical tests or rough handling, although there is no outward sign. The elimination of the cement next to the flange and the substitution of a sanded surface in place of the grooves for holding the cement greatly reduces the maximum stress.

To the right of Fig. 7 is shown a failure in an insulator of similar design but of different material. These insulators have transverse cracks in the bottom of the grooves, showing that the insulators would not withstand the elongation of the metal under the highest working temperature. A higher assembly temperature would improve this or preferably a sanded surface in place of grooves, for the latter would be free from the objection of high shearing stresses in cold weather.

A magnified view of a sanded surface is shown in Fig. 8. In addition to eliminating grooves which tend to concentrate both electrical and mechanical stress, this surface is of equal gripping efficiency in any direction. This latter property greatly reduces the maximum stress set up in insulators working under heavy mechanical loads.

As there are records of insulators working under loads which set up stresses of at least 50 per cent of the ultimate, it seems quite probable that most mechanical failures are due to stresses very much higher than have been thought possible.

It is possible that vibratory stresses which are most severe in dead-end insulators may cause a breakdown of the dielectric structure which, with the greater weathering, may account for the very much poorer showing made by dead-end insulators in some cases.

It is certain that, where the maximum stress is very high and fluctuating with temperature, it will be only a matter of time before the molecular structure of the dielectric will be destroyed. Where this is combined with an increasing stress from cement expansion it is apparent that failures may be very serious in time, although there is little evidence of this during the early years of operation.

While only defects from mechanical stresses have been con-

sidered, there are others of an electrical nature that are always present and in many instances are far more serious.

Good porcelain will withstand considerable heat, so material which acts as a resistor may pass electrical tests successfully, only to depreciate very rapidly in service owing to the absorption of water, which greatly lowers the resistance.

Porous material or that which lacks vitrification, while withstanding high voltages at time of installation, gradually loses its ability to carry electrical stress. Where the absorption is slight the insulator may have an appreciable amount of dielectric strength after a number of years, but where the absorption is large there will be little insulation in a year or so. On some of the earlier lines there was a large percentage of porous ware, which accounts for the poor operation until this material was weeded out.

An investigation of one of the large systems showed that out of 2 per cent of insulators shown to be weak by the megger, at least 1.4 per cent were poor owing to lack of vitrification, and could be detected by the trained eye.

Of the remainder, part were defective owing to porous streaks or the developing of faults left by the burning out of lint or other impurities. This really made the percentage of insulators which were poor, owing to conduction, over 1.4 per cent. It was not possible to classify some of the remainder outside of those having failed by cracking.

Fig. 9 shows a small fault detected by the megger and later burned by a very small current.

Porous insulators, while forming by far the largest percentage of defective members in the better designed insulators, can be detected to a large extent by Mr. Gaby's megger method and removed from the line.

For the factory use, it is advisable to use a more sensitive instrument than the megger in order to detect insulators which have very minute defects or are only very slightly deficient in insulation.

Fig. 10 shows a galvanometer which may be worked on a very high direct voltage obtained by rectifying and charging from the peak of the wave. Surface leakage has given considerable trouble, but it is hoped that improved means for shunting this surface leakage current will make this method very valuable.

Failures from electrical stress may be gradual, for it is possible to puncture porcelain several times, where the flow of current is

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FIG. 7

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FIG. 8

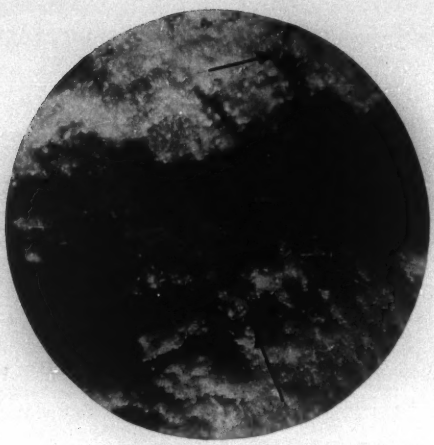

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FIG. 9

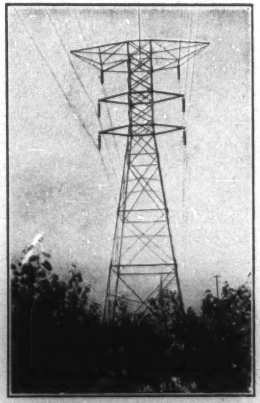

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FIG. 11

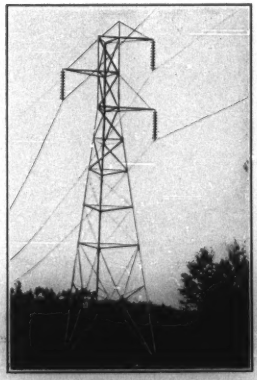

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FIG. 12

extremely small, before complete failure occurs. For this reason surges sometimes do considerable damage to a system and their effect is not noticeable until the cumulative damage causes a complete breakdown.

Since the static breakdown is in the nature of a very slight mechanical fault, it is not surprising that a comparatively low electrical or a mechanical stress will cause complete breakdown in time.

The success of some of the later types of insulators, however, shows that there is little to be feared from static puncture as compared to some of the other defects in the insulator.

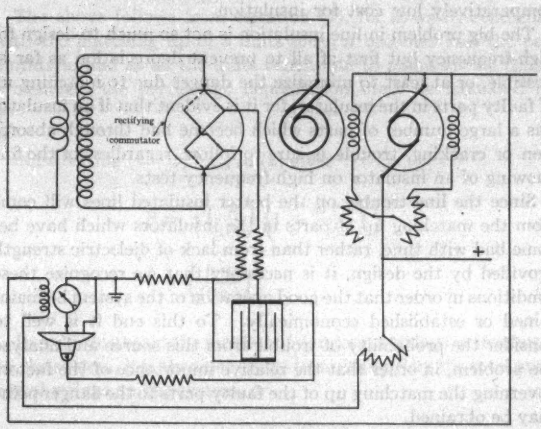

FIG. 10

In well-insulated lines, trouble comes not by the depreciation of the insulators as a whole, but by the matching up of defective parts in a single insulator or string such that the normal voltage or a switching surge causes the insulator to spill over or puncture. Just what the factors governing this are, was not apparent until some recent investigations caused this matter to be investigated and more thoroughly analyzed.

The investigation of some of the systems shows that there is practically no successive breakdown in the insulator, and that faulty members are about equally distributed throughout the string. This, with the total absence of punctures during several years' operation on lines like the Shawinigan Water and Power

Company, Fig. 11, and the 140-kv. Au Sable Electric Company's line, Fig. 12, shows that there is little danger of puncture from high-frequency surges where the insulator is made up of six or more closely spaced, well tested sections.

Lines of this class have also shown that the modern line is practically lightning-proof, for these systems have not averaged one kickout in two years from the spilling of insulators, from lightning or any other cause. This performance has, of course, been much better than was thought possible when the lines were insulated, and shows that spill-overs which have caused so much trouble on some lines can be prevented on a new system at a comparatively low cost for insulation.

The big problem in line insulation is not so much to design for high-frequency but first of all to prevent depreciation as far as possible, or at least to minimize the danger due to matching up of faulty parts in the insulator, for it is evident that if an insulator has a large number of parts which become bad through absorption or cracking, trouble is sure to follow, regardless of the fine showing of an insulator on high-frequency tests.

Since the line trouble on the better insulated lines will come from the matching up of parts in the insulators which have become bad with time, rather than from lack of dielectric strength provided by the design, it is necessary that we recognize these conditions in order that the good operation of the system be maintained or established economically. To this end it is well to consider the probability of trouble from this source and analyze the problem, in order that the relative importance of the factors governing the matching up of the faulty parts to the danger point may be obtained.

Let p = per cent depreciation, or average number of parts bad in 100.

n = number of parts or disks in the insulator or string,

b = number of parts which may be bad in a single string when danger point is reached,

$g = (n - b)$ = number of good parts in insulator when danger point is reached,

P = probability of a string being dangerous,

N = number of strings on the system.

From the theory of probabilities it follows that the probability of all the parts in a given insulator being faulty will then be

$$P = \left(\frac{p}{100}\right)^n \tag{1}$$

Switching surges, however, will usually spill or puncture several parts, so it is necessary to assume a dangerous condition when only a portion of the insulator is bad. Equation (1) is then important only when the line is insulated with a single part or has not carried voltage.

Where the danger point is reached when there are b parts bad, the probability of a string being dangerous becomes

$$P = \left\{ \left(\frac{p}{100}\right) \left(1 + \frac{g}{b}\right) \right\}^b \tag{2}$$

The above follows from equation (1), for as we are concerned with the matching up of b units only, n becomes b in the permutation, and as all the units contribute to make up the faulty b members the percentage depreciation must be increased by $\frac{g}{b}$.

Substituting $(n - b)$ for g in (2) gives

$$P = \left\{ \left(\frac{p}{100}\right) \left(1 + \frac{n-b}{b}\right) \right\}^b \tag{3}$$

$$= \left(\frac{p\,n}{100\,b}\right)^b \tag{4}$$

In order to obtain the number of dangerous strings or insulators on the system, it is then necessary to multiply P by the total number of strings on the system, or

$$NP = N\left(\frac{p\,n}{100\,b}\right)^b \tag{5}$$

gives the probable number of dangerous strings on the system.

In Fig. 13 are shown some curves where the minimum insulation is maintained for various number of parts n in the insulator. These curves show that a line having only 2 per cent depreciation and a switching surge that would spill two parts would have 30 dangerous strings in 1000 strings, where there were only three sections in the insulator. The addition of another part, however, reduces this hazard about 95 per cent and the addition of still another part reduces the probable dangerous strings to 0.064 in 1000 strings.

These curves show the economic importance of having a sufficient number of parts in the insulator in order to produce reliability.

Operation bears out these curves, for systems which were under-insulated have been very greatly improved by slightly increasing the insulation.

In Figs. 14 and 15 is shown the effect of varying depreciation

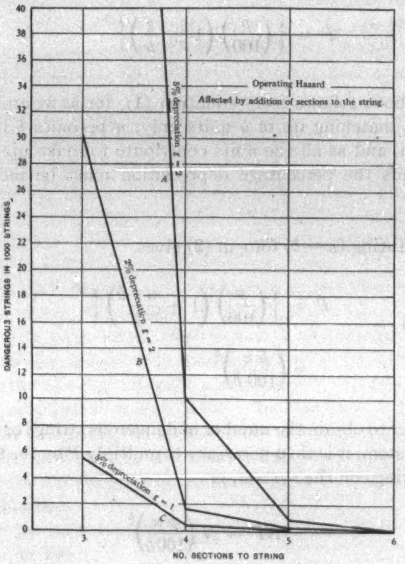

FIG. 13

for different insulators where the number of parts and minimum possible insulation is constant.

These curves show that the operating hazard increases very rapidly with the increase in the rate of depreciation, particularly for insulators which have only a small margin above the switching surge. It is also apparent that the reduction in the magnitude of the switching surge which allows an increase in *b* for a given insulator will greatly improve the operation of a system.

This point should not be overlooked, for it is of considerable economic importance, as resistance or reactance in the switch costs but little compared to an increase in the total insulation of the system. The curves also show that the advantage gained by building up the voltage and the elimination of the switching surge should not be underestimated, particularly where the system is having trouble.

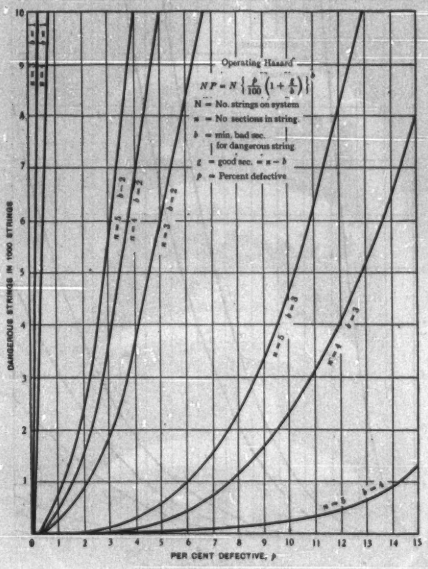

FIG. 14

Space will hardly permit at this time of a thorough discussion of the relative economic importance of the effect of depreciation, number of sections, or the magnitude of switching surge on the reliability of the system, but the curves will give a very good idea of the vast importance of the matching up of defective insulators in producing line trouble.

Where the depreciation is due to porous material, "meggering" of the line will weed out this material and the operation will be

greatly improved. If, however, the internal stress in the insulator is high, causing the insulator to fail at an increasing rate through cracking after several years' operation, it is evident that it may become very difficult to maintain the best of operation unless the line is gone over quite frequently. Trouble from the latter will be lessened by distributing new insulation uniformly throughout the different insulator strings.

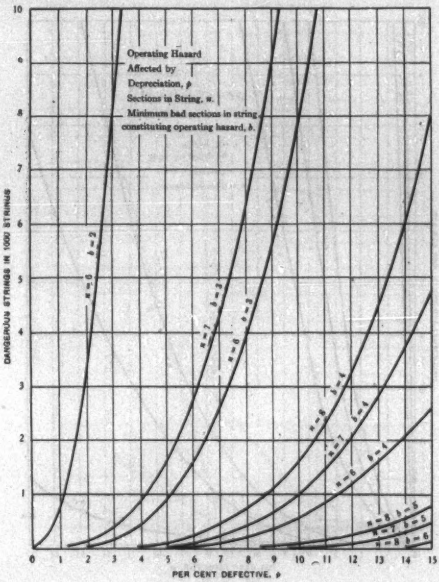

FIG. 15

Since the trouble on the line comes not from the insulator of average strength but from the insulator having the large number of weak members, it is highly important that the characteristics of the weak insulators be given careful consideration.

It must be remembered that even though the insulator is subjected to a flash-over voltage, the probability of failure decreases with the increase in the number of sections in a closely spaced insulator and that a large insulator may operate under very severe

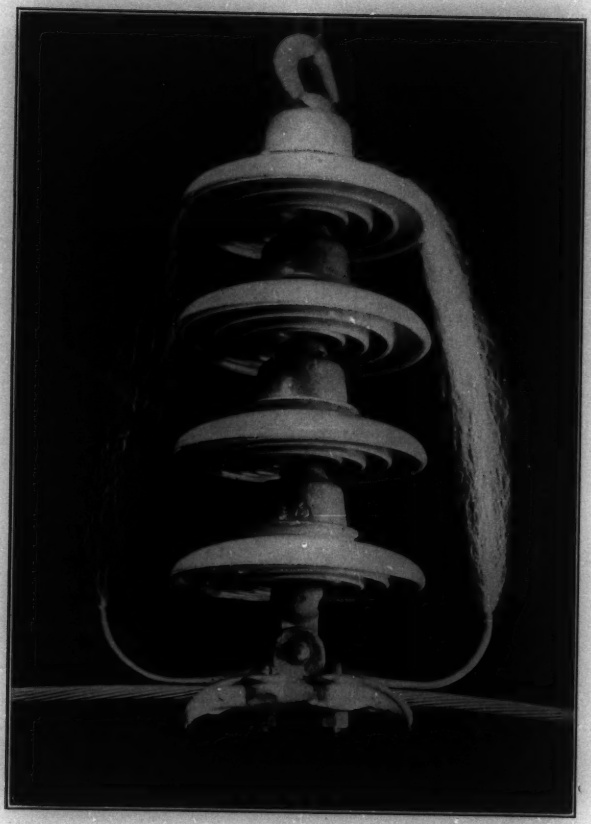

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FIG. 16

conditions, while an insulator composed of a few sections may fail, owing to lack of sufficient factor of safety, although the flashing voltage was much lower.

Since we have plenty of evidence to indicate that there is little to be feared in the large insulator, it is apparent that where failures occur it is usually due to the lack of factor of safety in the remaining good insulators in a string.

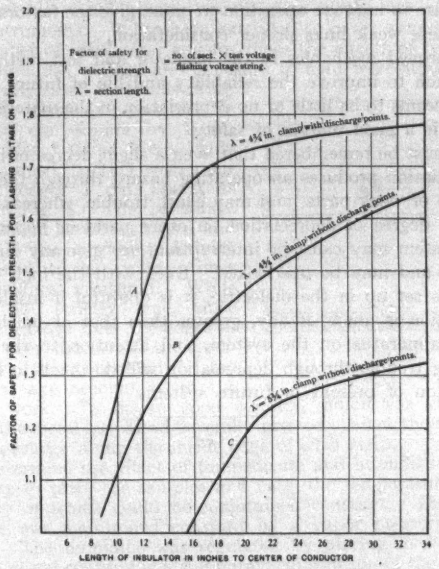

FIG. 17

The use of discharge horns and very closely spaced insulators improves the factor of safety for an insulator having only a few units. The insulator of this type is shown in Fig. 16. Fig. 17 shows curves based on this insulator and it is apparent that while the discharge points on the clamp greatly improve the factor of safety for a few units they do not materially improve the factor of safety for a long string. Since, however, depreciation is likely to reduce the total number of good units in a string, it is advisable

to use the discharge points in order that the remaining sections will tend to flash over rather than puncture.

It is not advisable, however, to obtain a very high factor of safety in this way, otherwise there may be too many spill-overs on the line, causing interruptions which may be even more serious than punctures where the discharge points were not used.

It becomes more apparent every day that a transmission line is like a chain in that it is no stronger than its weakest links, and if we are to improve operation we must give the factors governing these weak links proper consideration.

Improved mechanics in the insulator and test methods will do much to improve the reliability and life of future lines, as there seems to be little or no depreciation in the material where there is a good margin of safety.

It must be remembered that even a slight degree of insulator depreciation produces an operating hazard through the matching up of weak parts, and may cause trouble, whereas a much higher degree of depreciation on other parts or apparatus on the system may cause no interruption, nor give any direct evidence, and may be overlooked. Even with the high working stresses set up in the dielectric, it is doubtful if insulator depreciation is much, if any, greater than that of much of the other apparatus on the system, and attention to the factors causing trouble through depreciation will do much to improve operation of present or future systems.

DISCUSSION ON "EFFECT OF ALTITUDE ON THE SPARK-OVER VOLTAGES OF BUSHINGS, LEADS AND INSULATORS" (PEEK), AND "INSULATOR DEPRECIATION AND EFFECT ON OPERATION" (AUSTIN), NEW YORK, DECEMBER 11, 1914.

Harvey L. Curtis: For many years it has been known that there may be considerable leakage over the surface of insulators. However, it is only within a comparatively short time that quantitative measurements have been made. The present investigation* was undertaken to determine the conditions under which leakage would become troublesome in the use of electrical instruments. It has been extended to cover a considerable number of insulators; and for these the effects of temperature, humidity, voltage and exposure to light were studied.

The samples of materials were obtained, whenever possible, in plates 10 cm. square by 1 cm. thick. Metal strips 1 cm. wide were clamped to this with their adjacent edges 1 cm. apart, as shown in Fig. 1. The resistance was measured between strips *A* and strips *B*. The surface resistivity is assumed to be twenty times the resistance measured. While this is not strictly true, since there is leakage over the edges as well as over the face of the specimen, yet the correction is too small to take account of in the present work. To insure good contact, tinfoil was wrapped around the metal strips and carefully pressed against the surface of the insulator along the inside edge of each strip.

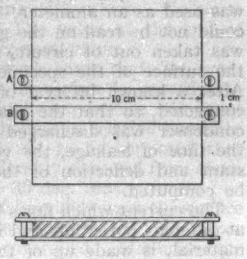

FIG. 1

To determine the effect of temperature and humidity it was necessary to place the samples in a case, the temperature and humidity of which could be maintained constant. The temperature was maintained constant by a vapor pressure thermostat. The humidity was regulated by placing in the case an open vessel containing a sulphuric acid solution of the proper strength to give the desired humidity. The air was thoroughly stirred by an eight-inch fan, the driving motor being outside of the case. The leads to the specimens were brought out through blocks of paraffin on the top of the case. These were melted together, so that the case was sealed almost air-tight. A glass window permitted the reading of the temperature and humidity.

The humidity was measured by determining the temperature at which dew would form on a polished metal surface. The

*A paper, entitled "The Insulating Properties of Solid Dielectrics," has been published as Scientific Paper No. 234 of the Bureau of Standards.

deposit of dew was usually obtained by circulating cold water through a metal tube, but for very low humidities it was found necessary to use alcohol in the tube and cool it by adding carbon dioxide snow.

In measuring the resistance, high accuracy was not required. An accuracy of 10 per cent was considered sufficient. As a large number of samples were measured, and each sample measured several times, it was necessary to arrange the apparatus so that it could be worked rapidly. To do this a condenser of suitable capacity was connected in parallel with a sensitive galvanometer. The galvanometer, which had a wide range of shunts, was placed directly in the circuit with the battery and resistance to be measured. If the current was sufficient to produce a readable deflection, the galvanometer was used as an ammeter. If the current was so small that it could not be read on the galvanometer, the galvanometer only was taken out of circuit, and the current which flowed over the surface of the specimen, was collected on the condenser. After a known interval of time the galvanometer was again connected, so that the charge which had accumulated on the condenser was discharged through the galvanometer. From the time of leakage, the voltage of the battery, and the constant and deflection of the galvanometer, the resistance can be computed.

The current which flows between two conductors, maintained at different potentials and insulated from each other by a solid material, is made up of two parts; that which flows through the insulator proper, and that which flows through a film of moisture or other conducting material on the surface of the insulator. The relative importance of these will depend on the resistance of the two paths. Since water, even if very pure, conducts much better than the ordinary solid insulators, a very thin film of water may have much less resistance than the insulator.

Before discussing these further, some definitions are desirable. The volume resistivity, ρ, of a material is defined as the resistance between two opposite faces of a centimeter cube. From the relationship between the size and the resistance of a specimen it follows that

$$R = \frac{\rho l}{A} \text{ or } \rho = \frac{RA}{l}$$

where R is the resistance of a cylinder of cross-section A and length l. By analogy we shall define the surface resistivity as the resistance between two opposite edges of a surface film which is one centimeter square. If the film is uniform over a surface

$$\sigma = \frac{R'b}{l}$$

where σ is the surface resistivity and R' the resistance of a rectangle of the film of length l and breadth b.

Since our measurements show that the surface film is largely moisture condensed from the surrounding atmosphere, the atmospheric humidity will largely determine the surface resistivity of a material. However, it is to be expected that the temperature of the specimen will be of some influence. Also since chemical changes are often produced by exposure to light, the surface resistivity of a material may be affected by such an exposure.

It might be expected that the applied voltage would affect the surface resistance, but, though voltages from 2 to 200 were used in some cases, no change in resistance was observed. At high humidities the resistance frequently changed by as much as a factor of 10 in the first minute after closing the key—increasing with some samples, decreasing with others. No cause for this behavior has been found. The value at the end of one minute has been taken as the correct value.

The results of our experimental work show that, for practical work in the laboratory, changes in surface leakage due to changes in temperature are of so little importance compared to the changes in resistance due to changes in relative humidity that they may be neglected. It is not to be supposed that this will hold for temperatures considerably removed from those used in this investigation; viz. 20 to 30 deg. cent.

In order to determine the effect of humidity upon the surface resistance, a number of samples were placed in the case whose temperature and humidity could be controlled. Measurements of the resistance were then made, but with an interval of at least one day after each change of humidity. After computing and tabulating the results, a curve was plotted for each sample showing its change of surface resistivity with the humidity. Nearly two hundred such curves have been plotted. From these, the curves given at the end of this discussion were selected.

Except in a few cases where it was desired to show the effect of cleaning, the samples were cleaned in the same manner and to the same extent as would be done in practical work; *i.e.*, they were wiped with a cloth or dusted with a brush.

All of the curves of surface resistivity are plotted on the same scale, so that they can be readily compared. In order to make this possible, the logarithm of the surface resistivity is plotted as ordinate, so that the actual values of the surface resistivity progress by powers of 10. In this manner very large changes of resistance can be shown on one sheet. The abscissa is the per cent of relative humidity.

Exposure to light may produce a chemical change at or near the surface. This chemical change may change the appearance of the material as well as the surface resistivity. However, there does not appear to be any connection between the two. Some samples, which show a very pronounced change

in appearance, show very little change in surface resistivity, and the reverse is sometimes the case. As the chemical changes produced by sunlight take place very slowly, the number of specimens examined has been limited. The major portion of the work has been done upon hard rubber, where the changes take place rather rapidly.

In Fig. 2 is a curve showing the change in surface resistance of a sample of hard rubber which was exposed to sunlight. In July 1908 the sample, which had deteriorated, was cleaned by washing in distilled water. This restored it to its original value, but the deterioration again proceeded rapidly.

The deterioration of some other materials when exposed to sunlight has been studied. In general it may be said that in no case is the deterioration as rapid as in the case of hard rubber. In some cases no effect has been observed.

In conclusion it may be stated that the surface leakage of

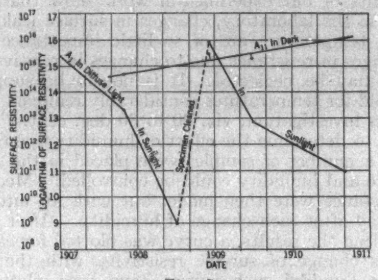

FIG. 2

the majority of materials varies greatly with the humidity of the surrounding air. This is due to the film of moisture which is condensed upon the surface. Any condition which, at a given humidity, will decrease the condensation of moisture or which will decrease the conductivity of the water will increase the surface resistance.

In Fig. 3 are given curves of four samples of hard rubber. Two had been protected from the action of the light, while two had been exposed to strong sunlight for several months. It will be noticed that between 0 and 50 per cent humidity the new rubber changes but little, while above that the changes are very pronounced. The surface resistivity is one *million* times as large at 50 per cent humidity as at 90 per cent. With the rubber which had been exposed to the light the changes in resistance continue until the lowest humidity is reached. The resistance of these specimens at very low humidity is 10^{11} times or one hundred billion times as great as is the resistance at

95 per cent humidity. It will be seen that very slight changes of the humidity will affect the insulation in a very marked manner.

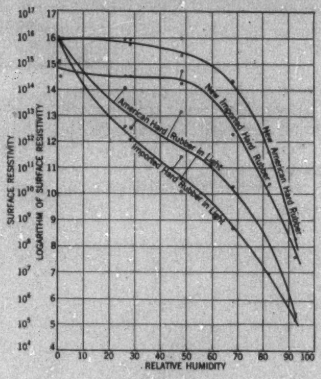

FIG. 3

Other samples of hard rubber have been tested, and those given may be taken as representative of the best grades of hard rubber. Of the two kinds whose curves are given, the imported rubber has a finer texture, and can be worked and polished

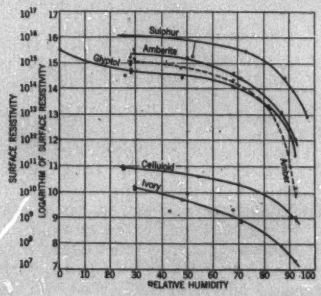

FIG. 4

better than the American rubber. However, all the tests upon the insulation show that the American rubber is the better insulator. This shows how difficult it is to connect the insulating properties with the mechanical properties.

Three of the curves given in Fig. 4 are for amber and amber-like materials. The sample of amber was a piece of clear native amber, the surface of which had been carefully polished. This is one of the few cases where only a single sample was measured. The amberite was a sample of the material which is made by compressing scrap amber. This material under the name of amberite or ambroid is now extensively used and it is apparent that so far as surface leakage is concerned it is the equal of native amber. In working with this material it was found that the specimen must be well cleaned to get the best results. Apparently handling with the fingers leaves a deposit of various deliquescent salts which condense moisture and lower the conductivity at the higher humidities. The glyptol is an artificial resin, resembling amber.

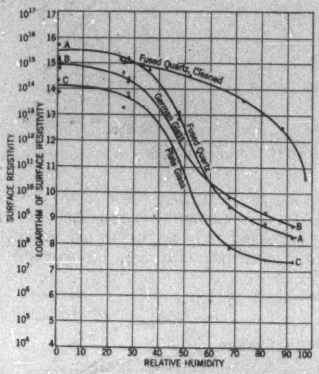

FIG. 5

Three different samples of sulphur were tested. They showed wide variations. The curve which is given lay between those of the other samples. Threlfall states that sulphur heated just to its melting point and then cooled has better insulating properties than that which has been heated to a higher temperature before cooling. The sample of celluloid was a piece of clear celluloid. Several samples were tested having various amounts of coloring matter and filler, but the surface resistivity was substantially the same for all. Ivory can not be considered as a material having high insulating properties. A substitute, white galalith, is somewhat better.

In Fig. 5 the behavior of fused quartz and certain kinds of ordinary glass is shown. Several samples of quartz were tested, but the two curves given were for the same sample. The

sample from which the curve marked "fused quartz" was obtained was cleaned in the same manner as other samples, but no special care was taken. It was then carefully cleaned in strong chromic acid, washed in distilled water, and dried before obtaining the curve marked "fused quartz, cleaned." The surface was thus well freed from foreign substances. At low humidities there was no difference in the two specimens. At higher humidities there was a large difference, amounting to as much as a factor of ten thousand. This may be due to the lack of condensation of moisture on the cleaned specimen or to the fact that the water which is condensed has a lower conductivity. Doubtless both of these causes play a part.

The statement is sometimes made that the method of manufacture of fused quartz very decidedly affects the insulating properties of the product. This has not been substantiated by the results obtained in the course of this investigation.

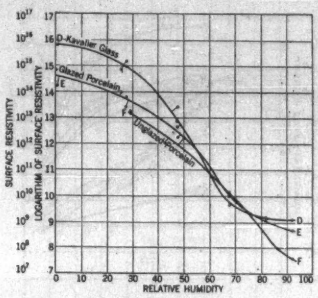

FIG. 6

A piece of old quartz tubing made by Heraeus in 1904 was measured at the same time and under the same conditions as the sample marked "quartz, cleaned." The results were practically identical. Another sample of inferior manufacture gave, under the same conditions, the same results as given by the curve marked "fused quartz."

The curves for three kinds of glass are given in Figs. 5 and 6. The Kavalier glass is a very hard combustion tubing having a large potassium and calcium content and a small amount of sodium. The German glass is a soft glass tubing such as is usually used in glass blowing. The plate glass was a piece from a plate-glass window. It will be noticed that the curves fall very sharply at about 30 per cent humidity, and that above 70 per cent humidity the change is not so marked. These samples were tested twice, with the results as given. Later they were cleaned with chromic acid in the manner described

for quartz and the resistances measured a third time. While the results did not show such marked changes as in the case of quartz, they were all in the same direction. Also the effect was most pronounced on the hard Kavalier glass and least so on the plate glass. It is known that the Kavalier glass is less soluble* than the other forms. Hence it is quite probable that the difference may largely be due to the difference in the conductivity of the water solution on the surface.

In Fig. 6 are also given curves for glazed and unglazed porcelain. The glazed porcelain was the base of a small porcelain switch, while the unglazed was a plate such as is used in chemical work.

In Fig. 7 are grouped the curves of some of the poorer insulators, together with some curves showing the effect of impregnat-

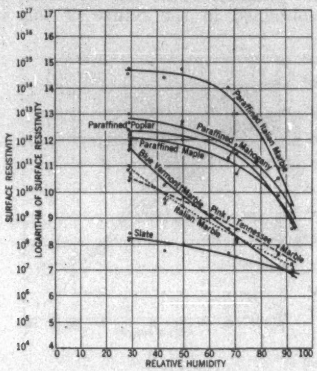

FIG. 7

ing them with paraffin. The slate was taken from the base of a switch and its origin is not known. The source of the marbles is stated on the curves. All were free from metallic veins, and were the equal of any that are used in switchboard construction. It appears that the coloring material in the Vermont and Tennessee marbles has very little effect on the surface leakage.

The marble and the different varieties of wood were impregnated with paraffin by keeping them in molten paraffin until no more air bubbles were given off. After cooling, the wood was planed and the marble sandpapered so that the resistance was measured over a surface of wood or marble with praffin filling the pores and not over a layer of paraffin on the surface.

*Hovestadt: Jena glass, p. 333.

The woods of more open grain, such as mahogany and poplar, show a somewhat higher insulation than the closer-grained maple.

The paraffined marble shows the considerable increase in the insulation that may be obtained by impregnating with paraffin. The surface does not present as clear and pleasing appearance as before paraffining, and it accumulates dust more readily. The marked decrease of the resistance with increasing humidity is not readily explained. One would expect that it would behave more like paraffin, which shows little change.

In Fig. 8 are given curves for various waxy materials. Ceresin is refined from the mineral ozokerite. It somewhat resembles paraffin, but has a higher melting point (69 deg.). An attempt was made to measure the leakage resistance of a sample at several humidities by the galvanometer method, using a distance of 1 mm. between the plates. It was impossible to obtain

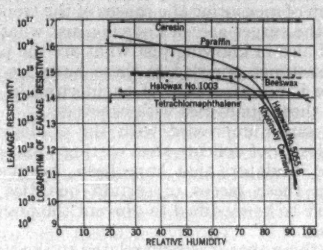

FIG. 8

a readable deflection, but it is certain the values are above those given in the curve. With the electrometer method the surface resistivity was still too high to measure, certainly above 10^{18} ohms. A special paraffin having a melting point of 58 deg. cent. also gave results too high to measure by any method at our disposal. A commercial form of paraffin known as parowax (melting point 52 deg.) gave the results shown in the curve. Measurements by the electrometer method gave a satisfactory check on these results.

The curve for beeswax was obtained from a sample of the yellow, unrefined material. White beeswax gave results which are almost identical. For these materials the surface must be fresh. They deteriorate quite rapidly when exposed to light and moisture.

The sample of tetrachlornaphthalene was furnished by Dr. Baekeland. It is doubtless a mixture of several isomers and may contain other chlorinated naphthalenes. It is about the consistency and color of yellow beeswax and has a very char-

acteristic odor. The samples of "halowax" are chlorinated naphthalenes. The sample No. 1003 is largely tetrachlornaphthalene. It is of a gray color, but in other respects has much the same properties, including odor, as the sample furnished by Dr. Baekeland. The sample 5055B is a higher chlorinated naphthalene, being largely hexachlornaphthalene.

The Khotinsky cement was flowed on a glass plate. The thickness was such that no appreciable part of the current flowed through the glass.

These waxy materials show the least change with humidity of any of the substances tested. This is doubtless due to the fact that the water does not wet the surface, hence instead of spreading over the surface is collected in minute drops.

D. B. Rushmore: In my opinion, the problem of insulator design must be solved by a scientific study of cement and a scientific study of porcelain; and by analyzing the elements, as we have in other problems, we will find out what is taking place, but the problem of measuring the causes of the trouble and knowing just what the surges are, in knowing just what the electrical forces are, and also in knowing just what are the physical conditions of the resistance opposed to these forces, is very difficult. Probably there is no other field of engineering in which it is so hard to get at these quantities with exactness.

I was very much impressed with the analogy of porcelain design to the design of delicate steel castings, and it was evident in some of the insulators that have been shown on the screen that, if casting these pieces of certain qualities of steel, the lines would have to be modified to prevent the undesirable forms of crystallization.

There is one thing that is closely related to the study of insulator application, and that is the practical necessity, both from an engineering and a commercial standpoint, of determining quantitatively the value of a ground wire. That has not yet been done, hundreds of thousands of dollars are spent every year in installing ground wires, and nobody knows of just how much value they are, and this cannot be determined by practical experience. It must be the result of the same kind of investigation that has solved the corona problem, and that, as Mr. Curtis has shown in the method he has worked out, must be by understanding the problem of surface leakage.

E. D. Eby: These data are not only interesting, but vitally important. They affect the design and operation of all electrical apparatus dependent upon air as an insulation. The "law of corona" was given to us some time ago, but the probable corresponding law for spark-over has not been generally appreciated.

Since the local corona point varies directly with the density, and the spark-over voltage approximately with the density, it appears that the same relative performance will occur at all densities. Therefore, an altitude rating is logical, safe and necessary. This was found desirable by the speaker about two

years ago in connection with transformer bushings, and has been applied in his practise since that time. The altitudes to be considered seldom exceed 10,000 ft. Several important installations exist at 4000 to 5000 ft.; a dividing line was set at 4000 ft., below which leads rated for 4000 ft. are supplied, and above which leads rated for 10,000 ft. are supplied.

In the cases of the leads which Mr. Peek has tested, the departure of the correction factor from δ amounts to as much as 15 per cent of δ at $\delta = 0.50$. This would be worth considering, as it represents a fair margin between factory test voltage and spark-over. But, since 10,000 ft. is the maximum altitude reached, except in very rare instances, the departure of the correction factor from δ (6 or 7 per cent) at that altitude is not worth considering, beyond treating it as an additional margin of safety.

An interesting detail of the tests on suspension insulators is the wide departure of the correction factor from δ in the case of one unit, amounting to 44 per cent at $\delta = 0.50$ in Table IV, compared with the close agreement in the case of two-, three- or four-unit strings. Perhaps Mr. Peek can add some explanations to these figures.

In putting into practical application the information given in this paper, it must be remembered that these tests were made at 60 cycles, and consequently are valuable chiefly in the degree in which they represent high-frequency performance. With the usual factors of safety in the design of leads, bushings and insulators, nominal frequency voltages would seldom, if ever, tax well-designed apparatus to the spark-over point of maximum elevation. It is, therefore, of primary importance that these data should apply to high-frequency voltage. It is known that different designs of leads and insulators perform differently under high frequency. Whether such differences may be expected to affect the altitude factor, perhaps Mr. Peek can tell us.

P. W. Sothman: Every time this very vital subject of insulation is touched upon, we are apt to have the feeling that we are getting further away from it, and I was afraid to-night that Mr. Austin might again change my mind in regard to certain conceptions I have had, but in many points I agree absolutely with Mr. Austin, particularly that, from a mere investigating standpoint, we should learn how to build an insulator. We have tried to teach and preach for the last few years that the insulator is one of the most important elements in the whole system; that it is as important as the generator or lightning protection, or a switch or anything else; still an insulator is chosen, because it will do a certain thing in a certain district, and it is assumed that it will do the same thing in another district, but, as Mr. Peek has pointed out, what it will do in New York it will not do in Denver.

In that respect I was very much pleased to see that Mr. Peek found a way of expressing to us here tonight, that the actual difference in altitude has an important effect on the insulator, and I think that anybody who has gone through Mr. Peek's

paper will see, as short as the paper is, and although it has been condensed to a very great degree, that the data given in it mean an immense amount of labor, and these two papers coming together this evening give us much light on the subject we are considering.

When we take the tests which have been made on insulators in the factory, and then consider the insulators which have failed out on the line, we see that we are absolutely unable to produce the same conditions, in our laboratory, no matter how we try, which agree with the conditions found in normal operation. We are trying to make high-frequency tests. We test an insulator at 25,000 or 50,000 volts, and then we raise the voltage higher and higher, until the child is killed, so to speak, and then we are satisfied. We think that the more power we can force through an insulator without apparent damage the better the insulator we get, but still we find in the case of insulators which will withstand a test, say, of 200,000 volts, in the laboratory, that when we take these same insulators and put them into actual service on a line which is carrying an operating voltage of say 50,000 volts, they will fail the next day, notwithstanding in our laboratory tests we considered them the best insulators that were ever made.

Now, gentlemen, that shows it is not the insulator, as such, that we have to blame for this condition, but there are other elements to which we must look for an explanation of this trouble. Mainly it is the line. There are a number of elements involved, and the insulator is only one of them, important, yet small. If we should build all parts of the transmission line in the way they should be built, we would see that the present factor of safety of the insulator, which is a very high one at the present time, is better than in some of the other elements which are used in the transmission line.

There is one thing which is very gratifying to see, and that is that the porcelain manufacturers have actually made very great improvements in the quality of the porcelain which they produce—I would not say the insulators—but in the manufacture of porcelain they have made very great progress. When we recall how insulators stood up five years ago under what was considered at that time a very severe test, and we see how they stand up today, we conclude that we have learned at least how to make porcelain which will serve the purpose. It is very gratifying, but I would like these gentlemen to get a little busier still, and let them try to make still further improvements; and what strikes me forcibly is that we still find that the porcelain which is imported from Europe is in many respects ahead of our porcelain which is manufactured here.

When three or four years ago we were talking about the percentage of failures—which matter Mr. Austin has referred to in a very interesting manner in his tables—we found that the failures were pretty close to forty-eight per cent, whereas today the same kind of failures amount to more nearly 6 or 7 per cent. I

think if the transmission line engineers would cooperate with the porcelain manufacturers, and give them freely their observations, that we could still make substantial improvement in these conditions.

That brings up another point, and that has to do with these specifications for the insulator, as such. We are on the eve of determining whether we shall or shall not make specifications for the insulators, and in that connection I cannot urge you too strongly to be very careful, and I might even caution you to go very slowly, in adopting any rule in which so many phenomena are still involved, which phenomena are so little understood by so many of our practising engineers. There is danger that we may put into a law on this subject a great many things which may be a great handicap to the future development of the insulator.

Selby Haar: I ask Mr. Austin what his opinion is of the nature in which electrical and mechanical stresses in the strain insulator combine. Is it something like the different kinds of mechanical stresses in material, or is it something entirely different?

The reason I ask this question is that I have heard it denied in all seriousness that a strain insulator need necessarily consist of any more sections than an ordinary insulator.

Charles P. Steinmetz: We must not lose sight of the fact that, after all, the line insulator today is really in a very good condition. For many years the line insulator was the weakest link in our transmission system. It is not so today. It is rather one of the strongest links, as shown by great increase of breakdown in all other parts of the system, which formerly were protected by the line insulator failing, thus protecting the other apparatus. This is proper, because it is desirable that the line should be the last thing to break down. Breakdown in a station can be watched for, and can be located, but it is a more serious matter to have a breakdown out on a mountain peak, and then to have to hunt for it in the winter time, during snowstorms, etc.

The problem, then, is really not so much to improve the line insulator—although naturally we expect improvement—as to make sure that the insulator as it exists on the line gives as good results as possible for first-class regulation and maintenance of the insulator protection; in other words, there should be proper testing of the line insulators, and weeding out defective ones. The strains on the insulator are partly electrical strains and partly mechanical strains and that means testing them both for electrical and mechanical strains. From the electrical point of view the problem is, after all, a simpler one, for, although electrical engineering is much younger than mechanical engineering, the method of testing and the various operations are so much more accurate, that we can determine certain things with accuracy in matters electrical. Naturally, the condition of testing should be to test as nearly as possible under such conditions of electrical

stresses, etc., as break down the insulators on the line. We all realize that the normal line voltage and normal line frequency practically never break down the insulator, but that it is caused by very high frequency or sudden impulse, or combinations of both; and investigation shows that very often a high-frequency wave train is preceded by a single still higher impulse; thus, high frequency and impulse tests are needed.

While high-frequency testing has been recommended many times, it has one serious danger, namely, that most methods of producing high-frequency oscillations involve the use of electrical resonance, which does not give a definite, but an indefinite, voltage and constant current effect, and it is, therefore, only a question of the power back of it whether you will break down anything or not. Therefore, while high frequency is that method of testing most nearly representing actual operating conditions, it must be made by high-frequency oscillating current generators which give a definite and determinable voltage, and not by the use of resonance to raise the high-frequency voltage to some unknown quantity, determined by the strength of the apparatus, in which case the tests mean nothing. I refer to this latter method because it is the reason for most of the objection which has just been raised against promiscuous testing by high frequency. The proper method involves high frequency produced at definite and measurable voltage.

Not so favorable are the conditions for making the mechanical test. To some extent the mechanical quality can be determined by electrical testing. As has been pointed out in the papers, a test for porosity of the porcelain can very often be determined by resistance measurements. Experience has shown that a more reliable method in picking out mechanical defects such as flaws, porosity, etc., since it does not depend on the effect of humidity, is the use of high frequency for testing.

Unfortunately, there still remain the mechanical strains in the insulator, which may and do, as has been shown in Mr. Austin's paper, break down the insulators either immediately or through rapid deterioration, which the electrical test does not always show, and for which reliable mechanical tests have not yet been devised.

As you probably know, for some years great advantage has been derived from use of the polariscope and polarized light to test for mechanical strains glass apparatus used for electrical purposes. Sometime possibly a similar method may be developed of using light in some form or radiation by which porcelain will be made transparent—X-rays, or some similar process—and show by polarization the internal strains of the porcelain, but we do not have that at the present time.

Assuming that we have reasonably safe methods of eliminating defective insulators, there remains the depreciation to be taken care of, which is to some extent accomplished by a careful study of the design and performance of the insulator, the material of which it is made, and the method of its application.

The reliability of service given by the transmission line, as you have seen from this paper, depends upon, and can very greatly be increased by an increase of the number of units, that is, an increase of the factor of safety. The increase of reliability is greatly out of proportion to the increased margin of safety, because it is not the effect of the margin, but the probability law, which makes it much more improbable in the case of individual insulators that their strength will fall below the stress.

The second method described of increasing the reliability is to reduce the surging. The third method is to reduce the depreciation.

There is really a fourth method, which has not been referred to in the paper, and is in reality included in the last one, or reduction of depreciation, namely, weeding out insulators on the line which become defective. If there is a ten per cent depreciation in five years, by testing the insulators on the line once a year, three-quarters, say, of those which have deteriorated, can be weeded out and the average depreciation will be reduced to a small fraction of what it would have been, if all those insulators had been left in the line; this would, therefore, greatly increase the reliability of service.

That brings us to one requirement which is very badly needed, and that is, reliable methods of testing the insulators on the line without taking them down; preferably, although it is not always essential, without taking the voltage off the line. Such methods would be principally valuable in high-frequency tests, because while in the case of high frequency we deal with considerable power, we do not have to guard against leakage by moisture, as in resistance measurements, and it appears advisable to make systematic tests of the insulators on the transmission lines, just as such tests of underground cables are made, by testing the insulators, disk after disk, insulator after insulator, at fixed intervals, and thereby detect and weed out those which have deteriorated. This method would greatly increase the reliability of operation.

E. E. F. Creighton: Mr. Peek has again added another element to his work on corona and Mr. Austin has not only described some valuable methods but has given us a new design of insulator.

Among the several things I should like to bring up regarding Mr. Austin's paper is, first of all, the sanding of the surfaces of the insulator to give the cement a grip on them. There is a very difficult problem involved in preventing the breakage of the insulators by the cement. If this very simple method is a solution of this problem it will mean a great advance in the production of good insulators.

Many tests on the chunky insulator in Mr. Austin's illustrations show a considerable advance in the design of insulators. Even at high frequency the design is such as to overcome, to a very great extent, the creepage spark. The spark creeps down

over the upper surface of the porcelain, but has little tendency to follow the surfaces of the skirts, but jumps directly to the pin. This is an indication of better design in the insulator, as it is less liable to fail.

Before closing, I want to mention the relative values of the methods of testing, among them the megger, which was used, I think, first by Mr. Gaby, in Canada. The megger gives good results where moisture can enter in the crack that is produced. If the crack does not extend all the way through the porcelain the megger is useless. If the moisture is dried out, as it usually is in pin type insulators, it is also useless. I have made tests first with the megger and then with high frequency, which showed that the megger results agreed closely with the high frequency results when moisture in the fault was present.

The direct-current test at high voltages which Mr. Austin mentions I have also used a number of times without any very great amount of success. We have gone at it with rectified currents at very high values of potential, but the trouble is that the air itself begins to leak and the current through the air is so great as to make the leakage through the insulator negligible. It is not the leakage over the surface of the porcelain, because the same leakage takes place when the insulator is removed. This method of test is of value only in special studies.

The third method, which I have had occasion to speak of several times, is the use of the high-frequency transformer. No matter if the fault is due to underfired porous porcelain, or whether there is a tiny flaw somewhere in it, the high frequency will bombard the air in the internal part and will develop these flaws. At the same time the high frequency, properly applied, is quite harmless to good porcelain. In testing porcelains the flaws are weeded out during the first few minutes, or very often in the first few seconds, and then the test can be carried on for fifty hours continuously without any more failures.

Farley Osgood: Mr. Austin brought out the fact that the value of the overhead ground wire should be considered in insulating the line, and he put that value in your minds only from the insulating and protecting standpoint.

I wish to put into your minds the fact that the overhead ground wire has a very distinct value in assisting in the locating of defective insulators, and that in making calculations on the construction cost of transmission lines, you should take that particular point into your calculations, and not consider the value of the overhead ground wire wholly from an insulating or protecting standpoint.

Our experience leads us to believe that the overhead ground wire is worth more as an aid to the operation of the line than it is as a protective device, and by its use, with the proper test instruments behind it, faulty insulators can be located within a few spans, and sometimes exactly, which fact is especially helpful for operating companies whose practise is to test out

lines with a view to locating faults and curing them when the lines can be relieved from actual service. The cost of an overhead ground wire of stranded steel or copper-covered steel will, in most cases, be a little more than one of the phase wires of the transmission circuit, assuming the phase wire not to be in excess of 250,000 cir. mils.

F. W. Peek, Jr.: I agree with Mr. Austin that most insulator failures occur due to small cracks in the porcelain caused by local mechanical stresses. These local stresses may be due to expansion of cement or metal parts, improper shaping of porcelain parts, etc. The so-called deterioration of porcelain is due to the gradual formation of these cracks. Electrical failure is finally the result. The following test, to show the above, may be given as an example: Six insulators, all of the same porcelain, but of different designs, were tested with 60-cycle, and with oscillatory voltages. Electrically they were excellent. These insulators were then placed in ice-water for one hour. This water was heated at the rate of 1 deg. a minute to the boiling point; it was then slowly cooled at the rate of 1 deg. a minute to room temperature. Cracks appeared in four insulators due to mechanical stress. Electrical failure occurred immediately upon application of voltage to these four units. The other two were not affected. They were then given a more severe test. They were put in water, which was gradually heated to the boiling point, and were then immediately plunged into ice-water. One failed, while the other remained intact. These two insulators were of the best mechanical design of the lot.

Other causes of failure, due to design and manufacture, are caused by occasional impurities getting into the mixture, porous porcelain, effects of tool marks on difficult designs, etc.

In selecting an insulator it is important: (1) to see that the mechanical design is such that local mechanical stresses cannot result and gradually produce cracking; (2) to see that the electrical design is such that local electrical stress tending to produce puncture will not result; (3) to see that the porcelain is not too porous and that the product is uniform. (1) and (2) are best determined by design tests, such as the one outlined here, and others which have been described in the A. I. E. E. PROCEEDINGS.* (3) is best determined by watching the product very closely in the process of manufacture. If the per cent loss in the routine test is large, or varies greatly, the product may be looked upon as suspicious and should be condemned until the cause of the failures is found. This per cent loss will not only be a check upon the quality of the porcelain but also, to some extent, upon design. For instance, if the design is so difficult that a large percentage of failures results in its manufacture, it should be condemned. I know of insulators that have been selected on a basis of per cent loss on one of the very high-voltage lines which have given practically no trouble.

* A. I. E. E. TRANS., this volume, p. 1107.

So far, only troubles due to design and manufacture have been discussed. Starting with *good insulators* operating trouble due to their improper use may result. An insufficient number of units in the case of the suspension insulator, or an insufficient "factor of safety" in the case of the pin type insulator, may cause trouble. At each high over-voltage lightning impulse, or high over-voltage surge impulse, an insulator may be damaged by local cracks forming in the porcelain. A puncture is started but has not sufficient time to develop; failure will result only after a number of impulses. Most of such troubles occur on the low-voltage lines, that is, on lines operating between 20,000 and 40,000 volts. What we know as the "factor of safety" of insulators is based on operating voltages and not on lightning voltage. It is thus not really a "factor of safety," as the lightning voltage is the voltage that causes failure. I have mentioned this in former discussions, but as it is a very important point I repeat it here. Lines operating at the voltages mentioned extend out into the same sort of country and are subjected to the same electrical stresses as the higher voltage lines; as the insulators are smaller, greater damage is done. In certain parts of the country there is practically no trouble due to this cause, when the number of insulators in a string exceeds a given number. In an exceedingly severe lightning country this number is seven to eight units. It must be realized that troubles due to this cause can only be eliminated by making the "factor of safety" on the low-voltage lines relatively higher than on the high-voltage lines.

Regarding tests there is one point I should like to make. It is unfortunate that practically all voltages differing from 60 cycles are termed "high frequency" and practically all troubles are attributed to "high frequency." An impulse, or an oscillation, or a wave of steep front, or continuous high frequency, etc., are all given under the same heading. Naturally their effects upon insulators are quite different and there is a great deal of confusion caused. To illustrate: the puncture voltage of an ordinary insulator may be 100 kv. at 60 cycles; at high frequency of 100,000 cycles from an Alexanderson alternator this insulator will break down at 5 kv., due purely to heating; an oscillatory voltage such as has been referred to in one of the discussions this evening will cause puncture at about 120 kv.; a single impulse, depending upon its wave front and duration, will cause failure at anything from 100 kv. to 1000 kv. or more. This readily shows how variable these effects are, yet all are said to be caused by "high frequency." The chief criticism of all such tests so far advocated is that they are absolutely indefinite. "High-frequency oscillation" testing is not a solution of the insulator problem; it is merely a means of testing, sometimes convenient, or sometimes useful as a supplement to the 60-cycle test.*

* A. I. E. E. TRANS., this volume, p. 1107.

I have recently made some tests using single impulses of a known wave front, length of tail, etc. Impulses with durations measured in microseconds or millionths of seconds have been used. Insulators will stand very high voltages when the duration is short. However, if the voltage is high enough some damage is done to the material. Perhaps a minute crack is formed; the effect is cumulative, and complete puncture results after a sufficient number of impulses has been applied. Such conditions actually occur on transmission lines.

E. D. Eby (by letter): In his paper on insulator depreciation, Mr. Austin points out that mechanical and chemical causes are chiefly responsible for insulator trouble which develops in service. Unequal temperatures in the dielectric, expansion of the cement by weathering or crystallization, and expansion of metal fittings, are mentioned as the chief causes. The paper and the discussion at the meeting dealt altogether with line insulation. I should like to ask whether in his experience Mr. Austin has encountered similar trouble with wall bushings, roof bushings or transformer bushings. It would appear that any of the causes for depreciation given might contribute to trouble with such apparatus as well as with line insulators. On the other hand, the construction of entrance and transformer bushings, particularly of filled types, is usually such that electrical weaknesses may not necessarily follow mechanical damage from cracks, etc. It would be interesting and instructive to learn the experience of manufacturing and operating companies along this line.

Edward J. Cheney (by letter): Insulator reliability becomes increasingly important as transmission distances increase and service requirements become more exacting. Such researches as that of Mr. Austin are, therefore, of the greatest interest and importance.

In one instance a large metropolitan community was absolutely dependent upon a certain transmission line. It was particularly annoying to all concerned to have the insulators on this line begin to fail with disconcerting frequency after they had given fairly good operation for several years and in spite of the fact that the lightning protection had been increased in the meantime. The remedy adopted represented the best which could be done at that time, but is suggestive of brute force rather than science. It consisted in putting on new insulators having a high-potential test double that of the original ones. The results have been good so far, but in the light of the information Mr. Austin has given us, it will now be possible to examine such problems more intelligently and we can be much more confident that the remedy will be permanently effective.

H. H. Sticht (by letter): No doubt the microscope is destined to be an important factor in the study of the insulator, just as it was in the study of iron and steel. Dr. Creighton and

Dr. Steinmetz mentioned the various methods for testing insulators, laying particular stress on the high-frequency and high-voltage tests. There is no doubt but that they are the most reliable tests that can be made in the test room, but how are they to be applied on the transmission line? If the line is one that is built through a level country they might be used. The transformers, with accessories such as a gas engine, and generator, could be mounted on a wagon and driven from tower to tower. But this can be done on very few of our transmission lines. It seems to me that in mountainous or undeveloped country, the megger method is the only one that can be used. I will grant that the method has its limitations, but so have the other methods. Mr. Sothman called attention to the fact that you can make a high-tension test on an insulator, place it on the line, and in a day or so it will break down under operating voltage. Mr. Peek has called our attention to some interesting information regarding the effect of high-tension impulses. Have we any guarantee that a high-potential test, at several times the operating voltage, does not produce a similar result on a small scale? The comparatively low voltage of the megger (1000 to 2000 volts) certainly cannot have any such bad effects. I believe that some of the bad reports about the megger have been caused by engineers trying to use it to detect faulty insulators of the pin type. However, one can readily see that it cannot be used for this class of insulators owing to the fact that a large enough surface cannot be obtained to which to connect the megger.

H. H. Schneider (by letter): In connection with the discussion of Mr. A. O. Austin's paper on insulator depreciation, attention was drawn to the partially defective insulator working in the transmission line. As the elimination of this insulator is of considerable importance, a few words on this subject might be of interest.

Consider any transmission line with its thousands or tens of thousands of insulators. The continual pounding of the elements, external stresses, and line surges, slowly but surely weaken the line insulators. Therefore, at any reasonable time after installation, we have in the line, insulators in every state—from the one as good as the day it was installed to the one on the verge of breaking down. Those in the latter class are of immediate concern, for although capable of withstanding normal potential, they break down when a surge or any abnormal condition arises. Of course, immediate replacing of the destroyed insulator is necessary when the breakdown causes a short circuit. Interruption to service, or the loss of a feeder for an indefinite period, results. Consequently, to make the transmission line as clear as is practically possible, it is incumbent upon us to weed out, systematically, insulators of this description by either periodic test or inspection.

I note that in attempting to weed out these partially defec-

tive insulators by means of applying over-potentials to the insulation of the line, it frequently happens that only one or two breakdowns occur upon each application. This requires the locating and the replacing of the defective insulators before the test can be further carried on. Where 15 to 25 bad insulators may be discovered in the course of a test of this nature, a great number of tests is necessary, with the result that the test drags over a considerable period. In order to expedite the test by the rapid replacing of the insulators located by test, men are generally posted along the transmission line right-of-way. Of course, a large number of men is required. Not only is this method of test far from satisfactory when a considerable number of defective insulators is on the line, but the expense connected therewith is also a heavy item. Further, where other live feeders are on the same pole as the feeder under test, the possibility that the arc will flash over to these lines when an insulator breaks down is ever present.

During the course of the discussion several gentlemen referred to the location of partially defective insulators by tests of a different nature. Mr. F. Osgood, I believe, called particular attention to their location through the medium of the ground wire. It would be of interest to have these gentlemen explain somewhat farther in this direction.

A very effective and comparatively inexpensive method of reasonably clearing a line of these insulators is by the following method of inspection. On a rainy night while the line is working under normal potential, the line should be patrolled. Partially defective insulators are readily detected by means of the arcing displayed. Close examination of the insulator can be made by means of high-powered field glasses, but this is only necessary in rare cases where the period between successive arcs is of considerable duration, thereby indicating that the insulator has but a slight defect or that arcing might possibly be due solely to the heavy precipitation. However, it is generally safe to treat this type of insulator as a defective insulator, for the combination of the heat produced by the arc and the rapid cooling of the insulator by the rain is gradually destroying it.

No matter how long the line, if a sufficient number of men is provided, practically all defective insulators can be noted in a single night. The number of times an inspection of this nature should be made depends entirely upon the locality and age of the line. However, three to four times a year is generally ample. Of course, no immediate change of insulators is made while the inspection is in progress, but all defective ones are noted and are replaced the next day.

R. P. Jackson (by letter): It becomes at once apparent that the whole indictment against porcelain is a secondary result of the fact that, for mechanical reasons, porcelain can be used only so as to avoid subjecting it to tension. This is the reason for the use of thin sections backed up by metal in such a way as to keep the porcelain in compression or shear. The ordinary

disk suspension insulator is a good example. It is molded into a shape to fit into a head or cap of metal with a metal pin in a re-entrant recess enclosed both by the porcelain and the metal cap.

This necessarily puts the porcelain under severe electrical stress to begin with. Further, unless the cementing is perfect and the coefficients of expansion just right, there are liable to be severe mechanical strains. All efforts to reduce the electrical stress by increasing the porcelain-filled space between the metal parts tends to weaken the mechanical structure of the unit by putting the porcelain under tension or bending moment.

Why not go the whole distance, however, and put the porcelain under direct tension in adequate section and thereby eliminate all trouble from puncture, by surges and lightning?

The chance of there being weak sections or units in a four-piece or five-piece insulator where each piece is only $\frac{5}{8}$ or $\frac{3}{4}$ in. thick is fairly high. On the other hand, what lightning would puncture lengthwise 20 in. of porcelain? Regardless of the so-called factor of safety, such an insulator must flash over rather than puncture.

What is the prospect of making a tougher porcelain, stronger in tension but perhaps of somewhat inferior specific dielectric strength, which would deliver us from turning to the laws of chance to see how much of our equipment is really worse than worthless?

Mr. Austin shows us, indeed, how to make the most of the materials and methods we now have, but at best the laws of chance do not furnish a very satisfactory method of picking out defective material, of which the degree of defectiveness is progressive.

A curious result of the laws Mr. Peek has investigated is the sparking voltage of lightning arrester horn gaps at high voltages in various parts of the country.

Judging from the reports that come back from operating companies, the various horn gap settings sometimes require much greater reduction and enlargement with low and high altitudes respectively than the density law would call for.

There has been a suspicion at times that some other cause, such as the presence of radioactive substances in the vicinity, must be necessary to account for the great horn gap settings required in certain territories. Of course, there may at times be some peculiarity of wave form which accounts for this and causes the discrepancy, but that is rather doubtful.

For example, it is our recollection that on 110,000 volts, settings of horn gaps ranging from four in. in one Western locality near sea level to 15 in. in another in the Rocky Mountains, have been found necessary.

SPECIFICATION AND ANALYTICAL PROCEDURE FOR 30 PER CENT HEVEA RUBBER INSULATING COMPOUND[1]

REPORT OF THE JOINT RUBBER INSULATION COMMITTEE APPOINTED BY A GROUP OF MANUFACTURERS AND USERS OF RUBBER COMPOUNDS, 1911-1914

PREFACE TO REPORT

I. Specifications for Rubber Insulation

A DEMAND for specifications which will enable purchasers of rubber insulation to secure good material on the basis of competitive bids has existed for many years.

In recent years, there has been no difficulty in securing insulation having the dielectric strength, specific resistance, elasticity and mechanical strength required in practise. Indeed, with the possible exception of dielectric strength, these qualities are usually in excess of actual service requirements. There is another quality, namely permanence, which although equally essential, has not been so easy to obtain.

While the physical properties of rubber insulation are susceptible of positive determination by tests which can be made before acceptance by the purchaser, the permanence of insulation can be ascertained only in practice, often at great loss, inconvenience and even danger. It, should, therefore, be the aim of specifications to overcome this difficulty and by some indirect means, ensure that the manufacturers supply compounds having the required endurance.

This obviously presents a difficult problem, as it requires that some relation be established between permanence and one or more of the properties which are susceptible of test. It has been established by experience that *Hevea* rubber or the rubber of the *Hevea Brasiliensis* tree, when properly cured, is a superior grade which is entirely satisfactory for electrical insulation. *Hevea* rubber may, therefore, be specified with advantage, although certain other rubbers of good quality may be excluded. The rubber has, however, to be further identified as *Hevea* rubber of good quality, the materials associated with it in the compound must be known to be non-deleterious and the compound itself must be well prepared, applied and vulcanized.

Two types of specifications have been devised to compass these restrictions. The first type of specification proceeds on the assumption that certain physical characteristics are developed to an unusual degree by the use of *Hevea* rubber, especially the grade known as fine *Para*. Among the qualities affected by the grade of rubber, and alleged to be useful indications of the presence of *Para* rubber, are the tensile strength,

1. This report has been referred to the Standards Committee of the A. I. E. E. for consideration, and was printed in the PROCEEDINGS at the request of that Committee.

elasticity and specific resistance. Accordingly some specifications have been issued in which one or more of these qualities is specified in an exaggerated degree. Experience has shown that such specifications are ineffective, as the specified physical quality can be obtained either by manipulation of poor compounds or at the expense of permanence in compounds made originally of good materials. In consequence of this, specifications based exclusively on physical tests have fallen into disrepute, but such tests now serve in modified form as adjuncts to other types of specifications.

The second type of specification to be considered is that in which a more or less rigid formula for the compound is specified and compliance with it exacted either by inspection during manufacture, or by chemical analysis supplemented by other tests of the finished product. Inspection which will really ensure compliance with such specifications is usually impracticable. Reliance must, therefore, be placed principally upon chemical analysis. Three difficulties at once arise. In the first place chemical analysis cannot *directly* ascertain the quality or quantity of the rubber which has been used in the manufacture of a compound; it can only determine these by the *indirect* method of measuring certain of its characteristic constituents. It is, therefore, necessary to present in the specification, a relation between the desired formula and the chemical findings.

The second difficulty is that in the past, chemists have employed diverse methods of analysis which give inconsistent results. It is, therefore, necessary to establish a satisfactory and standard procedure for analysis. The method of analysis must not only yield the information desired, but it must also be practical and capable of yielding uniform results when applied to the same compound by different chemists. In order to secure this uniformity, it is important to describe the methods of analysis in detail.

The third difficulty has been the non-uniform interpretation of analytical results.

The specification hereinafter presented is of the second or chemical type, in which an endeavor has been made to meet the three objections hitherto urged against such specifications. It contains a table showing the range of analytical results that should be obtained from a good compound containing 30 per cent of high class *Hevea* rubber, and is supplemented by a detailed analytical procedure. The specification is not complete as given, it being necessary to add appropriate electrical and mechanical test requirements.

The specification presented in this report should always be used in conjunction with the analytical procedure. The latter will, however, serve for the analysis of any compounds of the 30 per cent *Para* type with mineral fillers, provided the interpretation is made to correspond.

II. Standardization of Specifications

The necessity of purchasing insulated wire under conditions of competitive bidding led the various departments of the government, the railroads and other large consumers, to issue specifications for rubber insulation. These specifications were based upon the individual experience or theories of a number of engineers, aided by suggestions from

some of the manufacturers. For several years no attempt was made to standardize these specifications, and much trouble was given to the manufacturers by the diversity of requirements contained in them. In 1906, the Rubber Covered Wire Engineers' Association, consisting of representatives of the leading manufacturers, prepared a specification which was offered as a standard. This was followed in 1911 by the revised specifications of the National Board of Fire Underwriters, which, however, call for a comparatively low grade of compound. The former specification, although the best that could be agreed upon at that date, was so defective as to afford little or no protection to consumers. The latter occupies a field by itself, and make no pretension to specifying the highest quality of compound. Consumers desiring compounds of great permanence, therefore, continued to use their own specifications, altering them from time to time, in accordance with the best information available, with a growing tendency to rely upon chemical rather than physical tests. Some difficulty was experienced in enforcing these specifications owing to the inability of chemists to make concordant analyses of rubber compounds. This matter reached an acute stage in 1911, when Mr. E. B. Katte, Chief Engineer of Electric Traction of the N.Y.C. & H.R.R.R. Co., invited a number of manufacturers and consumers to a conference in order to discuss the possibility of standardizing specifications and analytical methods for rubber insulation. This conference was held at New York on the seventh of December, 1911, Col. Samuel Reber of the U.S. Signal Corps presiding.

After a full discussion of the subject, a committee was appointed to devise a specification and an analytical procedure for rubber insulation, the committee to report at a future conference.

This committee, which was originally known as the Railroads Rubber Committee and later as the Joint Rubber Insulation Committee, worked at the problem assigned to it for two years and presented a report to a second conference which was held at New York on October 15th, 1913, Col. S. Reber again presiding. The report was unanimously accepted by the Conference and the Committee authorized to continue in existence for another year for the purpose of making any revisions that might appear necessary in its report, as the result of a year of experience with it.

The membership of the general conferences at which the committee was appointed and to which its report was submitted, consists of representatives of the following interests:

U. S. Signal Corps,
U. S. Bureau of Standards,
American Chemical Society,
Lederle Laboratories,
New York Central Lines,
Pennsylvania R. R.,
General Electric Co.,
Hazard Manufacturing Co.,
Simplex Wire & Cable Co.,
Standard Underground Cable Co.

The organizations represented in the committee have been unstinting in devoting their unrivalled resources to this work, which could not have been carried out by private enterprise.

While the acceptance of the report does not bind any of these interests to the official adoption of the specification and analytical procedure, most of the members were of the opinion that they would be adopted in due course.

The Association of Railway Electrical Engineers has adopted the specification in its standard wire specifications, and the Power Distribution Committee of the American Electric Railway Association has recommended its adoption by the latter association.

It is hoped by the Committee that other societies and users of rubber insulation will follow this lead and help to abolish the existing multiplicity of specifications and methods of analysis.

The Committee wishes to emphasize the preliminary character of the report and urges everyone interested in the subject to send to the Secretary any suggestions or criticisms which may be of value, so that such statements may receive consideration before the publication of the report in its final form.

The Committee also desires to express its thanks to the many gentlemen not members of this committee, who have participated in the work, especially to Messrs. D. A. Cutler, F. Dannerth, F. S. Deemer, F. A. Hull, M. M. Kahn, G. H. Savage and D. Whipple.

III. Rubber

Those who are not familiar with the nature and sources of rubber may find some difficulty in understanding the report. The following brief outline of these subjects is therefore given, containing the best information that could be gathered.

Rubber is derived from certain tropical trees, creepers and shrubs found chiefly in South and Central America, Africa, and Southern Asia. When certain species of these plants are tapped, a thick milky-looking fluid or latex exudes from them. This latex is composed of very minute oil-like colorless refractive globules. Besides these globules, called caoutchouc or rubber-gum proper, which have a chemical composition represented by the formula $(C_{10}H_{16})_n$, the serum contains resins, protein and other compounds. Rubber is the coagulated latex, consisting of rubber-gum admixed with these impurities.

Rubber is furnished in America principally by the *Hevea*, *Micandra*, *Manihot*, *Castilloa* and *Hancornia* plants, usually in the wild state.

In Africa the principal plants are the *Landolphia*, *Clitandra* and *Kickxia*, also wild.

In Asia, there are the *Ficus* in the wild state and the *Hevea* in the state of cultivation.

In the Amazon valley, there are numerous species of *Heveas*, of which the most important is the *Hevea Brasiliensis*. This tree furnishes the most highly esteemed quality of rubber.

The *Heveas* in the Brazilian forests are cylindrical trees of an ashy color, from 20 to 30 meters high, and attaining a diameter of from 0.80 to 1.20 meters.

The usual process of tapping these trees is as follows: Incisions are made at about 3 to 3½ meters from the ground, by means of a long-handled

hatchet. The object of this operation is to make the latex ascend from the roots, in an effort to repair the incisions. The milk that oozes out is mixed with bark and other impurities and is utilized to make an inferior grade of rubber known as sernamby. Two days afterwards, incisions are made 2 meters from the ground and tapping cups fastened at the lower part of them. The latex collected in these cups is said to be collected "prime" and furnishes the best rubber. On the following day, the process is repeated by making incisions about 7 cm. below the first, this being continued on successive days until the ground is reached.

The rubber is coagulated from the latex by smoking. This is accomplished by putting the latex on a spatula or flat stick, and holding it over a fire made from wood or Urucuri nuts, the smoke of which is rich in acetic acid and creosote or similar oily substances. The latex is thus dried in successive layers until a ball or biscuit weighing from 20 to 60 kg. is obtained. The smoke acts as a coagulant, evaporates the water and at the same time kills bacteria, which would cause decomposition. Rubber prepared in this way is known as "fine *Para*", but when the curds or semi-solidified latex deposited in the latex basin are incorporated with it, the quality is lowered and the product is known as "entrefine" or "medium fine". If these natural curds are collected separately, they are known as "coarse Para" or "sernamby", a name which, as mentioned above, is also applied to rubber coagulated on the bark of the tree. *Up-river Para* rubber is *fine Para* collected from the *Hevea Brasiliensis* trees in the head-waters of the Amazon and its tributaries.

The wild *Hevea* rubber of Brazil is shipped in biscuits which contain from 15 to 20 per cent of impurities, which can be removed by rolling and washing with water preparatory to use in manufacture. These impurities are absent from plantation rubbers, a circumstance which must be considered when the prices of wild and plantation rubber are compared.

Several kinds of rubber trees are raised on plantations, but the most important kind is the *Hevea Brasiliensis*. Just as the rubber of this tree in the wild state varies slightly in composition according to its habitat on the upper or lower reaches of the Amazon river, so in the cultivated state, a similar variation exists, but to a greater degree. The principal source of plantation rubber is Southern Asia.

The latex of plantation rubber is collected in much the same way as in the case of wild rubber, but coagulation is usually effected by the addition of chemicals. As such coagulation does not usually have the preservative effects of smoking, the better grades of plantation rubber are "cured" by exposure to antiseptic smoke.

The principal forms in which plantation rubber is prepared, are crepe and sheet, either of which may or may not be smoked.

In the preparation of crepe, the strained latex is poured into pails and a small quantity of acetic acid is added. This curdles the latex, the curds rising in the serum. The resultant curd is passed between steel rollers under a stream of water. From this process, the rubber emerges in long, thin, corrugated strips, having the appearance of crepe. The process is completed by drying.

For preparing sheet or biscuit, the latex is set in shallow pans, the acid added and the clot allowed to stand until it sets quite firm. The water

is then squeezed out and drying completed in hot rooms. The curds which do not rise with the main clot are made into an inferior grade of rubber.

Curing is effected by hanging the rubber in an atmosphere impregnated with creosoted smoke, thus antiseptizing the rubber. It should be observed that coagulation with acetic acid and curing with creosote chemically simulates the Brazilian process of smoking with the *Urucuri* nut.

Both wild and plantation rubber are used in the manufacture of insulating compound. It is claimed that some difficulty is experienced in obtaining a high tensile strength with some plantation rubbers, and their lasting qualities have not been established as well as those of wild Brazilian rubber. It is, therefore, desirable, where the greatest durability is to be insured, that the grade of rubber should be *fine Para* or a plantation rubber of good grade which is practically indistinguishable from it by chemical tests, when compounded.

Most high grade rubber compounds for insulating wire are prepared by mixing rubber gum with sulphur and mineral or organic fillers, such as paraffine wax, ozokerite, ceresine, zinc oxide, talc, whiting, litharge, barium sulphate, and basic lead sulphate.

These ingredients are thoroughly mixed on heavy steel rolls, after which the plastic compound is either pressed on to the wire through dies or applied in the form of a longitudinal strip which is pressed into tubular form around the wire.

The covered wire is then placed in a chamber or vulcanizer containing either steam under pressure, or heated air. The duration of this heat treatment varies from less than one hour to several hours, depending upon operating conditions and the temperature, which is usually from 120 to 150 deg. cent. Under these conditions the sulphur combines with the rubber to form vulcanized rubber. This process of compounding and vulcanizing changes the character of the rubber so that its strength, insulating qualities and durability are enhanced.

W. A. Del Mar,
P. Poetschke,
E. L. Willson.
Sub-committee on publication of report.

PRELIMINARY REPORT OF COMMITTEE

Part I —General Report.
" II —Analytical Procedure.
" III—Explanation of Procedure.
" IV —Specification.
" V —Explanation of Specification.

Part I—General Report

1. At the Conference of December 7th, 1911, it was resolved that a Committee be appointed to develop a means of specifying and analyzing rubber insulation, the Committee to report its findings at a future conference.

2. The Chairman of the Conference, assisted by other members, appointed the following to serve upon this Committee:

Mr. C. R. Boggs, Simplex Wire & Cable Co.,
Mr. W. S. Clark, General Electric Company,
Mr. W. A. Del Mar, N.Y.C. & H.R.R.R.Co.,
Mr. W. B. Geiser, " " " "
Mr. J. P. Millwood, Consulting Chemist,
Mr. P. Poetschke, Lederle Laboratories,
Mr. H. B. Rodman, Pennsylvania R. R. Co.

Later, at the request of the Committee and by unanimous consent of the members of the original Conference, the following were added:

Mr. J. B. Tuttle, U.S. Bureau of Standards,
Mr. E. L. Willson, Hazard Manufacturing Company.

The Committee thus constituted is composed of three railroad men, three independent chemists, and three representatives of the manufacturers. Of the nine members, seven are chemists and two are engineers.

3. The Committee immediately upon its formation decided to confine itself to the development of a specification and an analytical procedure for compounds of the 30 per cent *Para* type. In accordance with this policy it considered the available analytical procedures and developed several which formed the basis of further study. Samples of different rubber compounds were analyzed by these tentative methods. The results were unsatisfactory and the discrepancies were investigated. Subcommittees were formed to do much of this work. Twelve regular committee meetings, besides numerous sub-committee meetings, were held; thirteen different compounds were distributed to be analyzed by the entire committee, and many more compounds were experimented upon by the sub-committees and individual members.

4. The outcome of this work has been a gradual elimination of errors and the development of a procedure which, with experience, will give uniform and consistent results.

5. The Committee feels that the procedure which it has developed is not perfect and believes that it should be put into use for a year before being offered as final. With this in view the Committee hereby presents to the Conference, a preliminary procedure and requests the permission of the Conference to publish it and obtain the results of experience with it during the ensuing year. The Committee proposes to avail itself of the experience gained in this year and to incorporate whatever improvements it may decide upon in a final report.

6. The Committee has also made a study of specifications for rubber insulating compound. It presents herewith a chemical specification for a compound containing 30 per cent of *Hevea* rubber with mineral fillers and requests that this specification, like the analytical procedure, be considered as tentative.

7. There may still exist the possibility of making compounds which will conform to the specification when analyzed by the procedure, but which are not compounded as desired. The Committee believes, however, that the probability of such compounds being supplied is very small indeed. After more experience with the procedure it may be possible to narrow the limits prescribed in the specification.

Part II— Procedure for the Analysis of Rubber Compound

Object of the Analysis

1. The object of this procedure of analysis is to determine whether rubber compounds comply chemically with the accompanying specification which is intended to secure compounds containing 30 per cent of the best *Hevea* rubber, and mineral fillers.

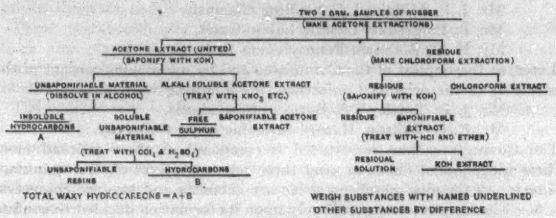

Diagram A.—Outline of Method of Rubber Analysis Exclusive of Fillers and Sulphur Determinations

Outline of Procedure

2. The general procedure is shown by the accompanying diagram A, which gives an outline of the separations to be affected by acetone and chloroform extractions, and saponification with alcoholic potash.

General

3. Make the analysis upon the insulation after vulcanization and, whenever possible, before the saturation of the braid. Wipe the insulation thoroughly with a damp cloth to remove any adhering material, but do not remove waxy hydrocarbons from the surface.

4. If, however, a saturated braided sample must be used, remove the braid and sandpaper the insulation to a depth of at least 5/1000 of an inch and wipe with a damp cloth. In such cases report the condition of the sample.

5. Perform all determinations in duplicate and take the average value arbitrarily as the true value. Duplicate determinations must check within the limits specified.

6. Make blanks on all determinations and deduct the results accordingly.

Sample

7. Remove the insulation entirely from sufficient wire to give a sample weighing about 25 grams. Cut this into small strips and grind slowly in either a No. O Enterprise coffee mill or a mill such as shown by the

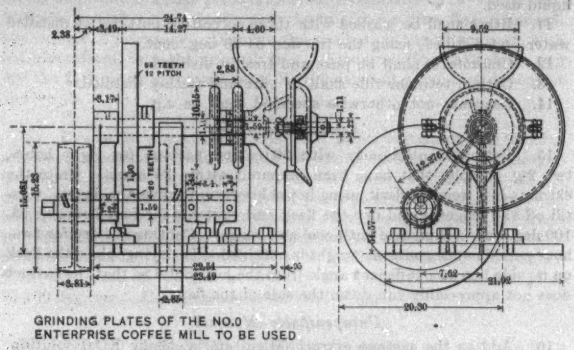

DIAGRAM B.—RUBBER GRINDER
(All dimensions in centimeters)

accompanying diagram B. Adjust the grinder so that not more than 20 per cent will pass through a 40-mesh sieve. Sift all the material through a 20-mesh sieve, regrinding what is retained on the sieve until the entire sample has passed through. The wires of the sieves shall be evenly spaced in both directions and shall be of 0.016 and 0.010 inches diameter in the 20 and 40 mesh sieves respectively. Remove with a strong magnet any metal that may have come from the grinder and thoroughly mix the sample.

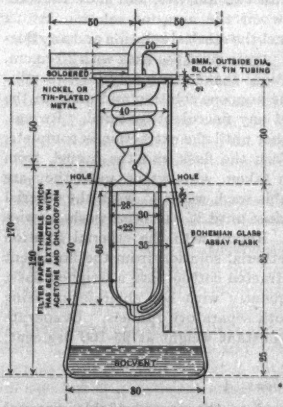

DIAGRAM C.—RUBBER ANALYSIS
EXTRACTION APPARATUS
(All dimensions in millimeters)

Extraction Apparatus

8. The extraction apparatus shall conform with the accompanying diagram C. It shall be heated so that the period of filling an empty syphon cup with acetone and completely emptying it, will be between 2½ and 3½ minutes.

Preparation of Reagents

9. Acetone shall be freshly distilled over anhydrous K_2CO_3 using the fraction 56-57 deg. cent.

10. Alcoholic KOH solution shall be of normal strength and shall be made freshly by dissolving the proper amount of KOH (purified by alcohol), in 95 per cent alcohol which has previously been distilled over KOH. The solution shall be allowed to stand for 24 hours and only the clear liquid used.

11. Ether shall be washed with three successive portions of distilled water and distilled, using the fraction 34-36 deg. cent.

12. Chloroform shall be pure and freshly distilled.

13. Carbon tetrachloride shall be pure and freshly distilled.

14. Reagents not otherwise specified shall be c.p.

Acetone Extraction

15. Extract continuously with 60 cu.cm. acetone for eight hours, two 2-g. samples that have been prepared within 24 hours. Unite the extracts in a weighed flask, using hot chloroform to rinse the flasks. Distill off the reagents and dry the flask and contents for four hours at 95-100 deg.cent. Desiccate until cool and weigh. Continue to dry for two-hour periods until constant weight is obtained. In drying, place the flask on its side but at a sufficient angle from the horizontal so that the extract does not appreciably run down the side of the flask.

Unsaponifiable Material

16. Add to the acetone extract 50 cu. cm. alcoholic KOH solution, boil under a reflux condenser for two hours, and evaporte to dryness, removing all alcohol. Add 10 cu.cm. water and 20 cu.cm. ether; heat until the wax etc. are in solution, cool, transfer to a separatory funnel, wash out the flask with warm water and then cool, finally with two 20 cu.cm portions of ether. The water volume should be 100 cu.cm. and the ether at least 40 cu.cm. Shake vigorously for two minutes, and allow the solutions to separate thoroughly. Draw off the aqueous solution into a second funnel, leaving in the first funnel the etherial solution and any flocculent material that may be present. Again rinse the flask with 20 cu.cm. ether and add it to the aqueous solution; shake vigorously for two minutes, and when separated draw off the aqueous solution and unite in the first funnel the etherial solutions and any flocculent material. Repeat, shaking with 20 cu.cm. portions of ether until the extraction is complete, using at least 120 cu.cm. ether. Wash the flask and the funnel, from which the etherial solution has been taken, with water, until they are free from alkali, subsequently using this wash water to wash the etherial solution. Continue washing with water until it has been washed twice after it shows no alkaline reaction. Retain with the etherial solution any flocculent material. Filter the etherial solution from the flocculent material, through a small pellet of extracted cotton, into a weighed flask, washing first with ether and subsequently with hot chloroform, using this to rinse the original flask and both separatory funnels. Evaporate the solvents and dry the extract to constant weight at 95-100 deg.cent; desiccate until cool and weigh.

Hydrocarbons A

17. Add 50 cu.cm. absolute alcohol to the unsaponifiable material and warm until solution is as complete as possible. Cool the solution to —4 or —5 deg.cent. and maintain at this temperature for one hour by pack-

ing the flask in a mixture of ice and salt. Filter out the waxy hydrocarbons, using a funnel packed with ice and salt, and apply suction if necessary. Wash the flask and filter with about 25 cu.cm. of 95 per cent alcohol, which has been previously cooled in the same temperature. Catch the filtrate in a flask which is afterwards cooled to —4 or —5 deg.cent. to make sure that all possible waxy hydrocarbons have been removed, and refilter if necessary. Dissolve the residue on the filter paper with hot chloroform, into the original flask. Evaporate the chloroform and dry the flask to constant weight at 95-100 deg.cent.; cool in a desiccator and weigh.

Hydrocarbons B

18. Evaporate the alcohol from the flask containing the alcohol soluble unsaponifiable material add 25 cu.cm. carbon tetrachloride and transfer to a separatory funnel. Shake with conc. H_2SO_4, drain off the discolored acid and repeat with fresh portions of acid until there is no longer any discoloration. After drawing off all the acid, wash the carbon tetrachloride solution with repeated portions of water until all traces of acid are removed. Transfer the carbon tetrachloride solution to a weighed flask; evaporate off the solvent and dry the flask to constant weight at 95-100 deg.cent. Cool in a desiccator and weigh.

Free Sulphur

19. Add two grams KNO_3 to the aqueous solution and washings from the etherial separation of the unsaponified material. Evaporate to dryness in a silver or nickel dish and heat to quiet fusion, avoiding contamination with sulphur fumes. Transfer with water to an evaporating dish, acidify with HCl, evaporate to dryness, and dehydrate silica. Add 2 cu.cm. conc. HCl, take up in water, filter and wash, making a volume of 200 cu.cm. Heat to boiling and add slowly a slight excess of hot 10 per cent $BaCl_2$ solution. Allow to stand over night, filter, wash, ignite, weigh the $BaSO_4$ and calculate to sulphur.

Definition of Terms Describing Compounds of Acetone Extract

20. The difference between the Acetone Extract and the Free Sulphur shall be called the Organic Extract.

21. The difference between the Organic Extract, and the Unsaponifiable Material shall be called the *Saponifiable Acetone Extract.*

22. The sum of the Hydrocarbons A and B shall be called the total *Waxy Hydrocarbons.*

23. The difference between the Unsaponifiable Material and the Waxy Hydrocarbons shall be called *Unsaponifiable Resins.*

Chloroform Extraction

24. Extract continuously the residue from one of the acetone extractions, (without necessarily removing the acetone that may be on it), for four hours with 60 cu.cm. chloroform, using a weighed flask. Distill off the solvent and dry the flask and contents for two hours at 95-100 deg. cent. Desiccate until cool and weigh. Continue to dry for one hour periods until constant weight is obtained. In drying, place the flask on its side but at a sufficient angle from the horizontal so that the extract does not appreciably run down the side of the flask. (If it is needful to wait after the acetone extraction, before starting the chloroform extraction, the sample must be kept in a vacuum of at least 50 mm. of mercury.)

Alcoholic Potash Extraction

25. Dry the residue from the chloroform extraction at 50-60 deg.cent., put into a 200-cu.cm. Erlenmeyer flask with 50 cu.cm. alcoholic KOH solution and boil for four hours under a reflux condenser. Filter the solution into a beaker and wash twice, using each time 25 cu.cm. hot absolute alcohol and then wash thoroughly with hot water. Evaporate the solution to approximate dryness, take up in warm water and transfer to a separatory funnel. Acidify with 15 cu.cm. 5 normal HCl, using this to rinse the beaker. Add sufficient water to make the bulk of the solution 100 cu.cm. When cool add 40 cu.cm. ether, using it to rinse the beaker in 20-cu.cm. portions. Shake the aqueous and etherial solutions thoroughly. After complete separation, draw off the aqueous solution and treat in another separatory funnel, with a fresh 20-cu.cm. portion of ether. Continue to shake the aqueous solution with fresh portions of ether until a colorless portion has been obtained, then shake out twice more. Unite the etherial solutions and wash with successive additions of water, continuing twice after the water shows no acid reaction. Filter through a plug of extracted cotton into a tared flask, wash the filter and funnel with ether, evaporate the ether without boiling and dry the residue to constant weight at 95-100 deg.cent. Cool in a desiccator and weigh.

Fillers

26. Extract a 1-g. sample with acetone for five hours. Transfer the residue to a tall lipped 200-cu. cm. beaker, add 40 cu.cm. terebene and 20 cu.cm. xylol and heat on an oil bath at 105-110 deg.cent. for about 20 hours, or until the bulk of the fillers settle promptly after stirring. Occasional stirring will aid the solution. Allow the beaker to stand until the fillers and undissolved residue have settled thoroughly and decant the supernatant solution into a beaker. Add to the undisturbed residue 30 cu.cm. terebene; heat for several hours, allow to settle, decant, unite the decanted solutions and repeat this treatment as long as there is any indication of rubber being present. Continue to heat the decanted solutions during the further treatment of the undissolved residue and filter them through a tared filter paper. This filter paper must be of close texture and shall have been washed with terebene, alcohol and acetone. The tare filter shall be treated with the same solvents and dried in the same manner throughout the analysis as the filter containing the residue. Weigh all filter papers in weighing bottles of sufficient size to take them without folding. Refilter if mineral matter runs through. Wash the beaker that contained the decanted solutions and the filter paper, with benzol, using a second beaker to catch the filtrate. Add benzol to the beaker containing the residue, heat and after settling decant, repeating this treatment with benzol until it is thoroughly washed. Filter and wash well with benzol. Wash in the same manner both beakers with hot alcohol and then transfer the residues to the filter paper, using hot alcohol and an acetone extracted policeman. Wash finally with acetone. Dry in air at 95-100 deg.cent. and weigh. Again wash the filter paper and contents with benzol and alcohol, dry, weigh and repeat this treatment until constant weight is obtained. Evaporate all the filtrates and washings, transfer to a porcelain dish, burn off and weigh. Add this amount to the fillers found above. If this ash is greater than 1 per cent, the entire

determination shall be repeated. Subtract 0.5 per cent as anarbitrary value for the amount of organic matter from the rubber retained with the fillers.

Sulphur in Fillers

27. Transfer the fillers from the filter paper into an iron crucible; burn the filter paper and add the ash to the crucible. Add the Total Sulphur flux and proceed with the determination of sulphur as in Section 28, Total Sulphur. Subtract the percentage of sulphur found from the percentage of fillers to determine the percentage of fillers free from sulphur.

Total Sulphur

28. Mix a 0.5-g. sample with 4 g. Na_2O_2 and 6 g. K_2CO_3 in a dry 15-cu.cm. iron crucible. Cover and heat gradually until the mixture fuses, proceeding cautiously, as rapid heating will cause an explosion, and then bring to quiet fusion for 15 to 20 min. Apply the heat so as to avoid contamination with sulphur fumes. Rotate the crucible while the melt solidifies. When cool, put crucible and cover into a casserole containing 200 cu.cm. of water; add 5-10 cu.cm. bromine water and boil until the melt is dissolved. Allow the precipitate to settle, decant the liquid through a thick filter and wash the residue with hot water. Acidify the filtrate with HCl, evaporate to dryness and dehydrate silica; add two cu. cm. conc. HCl., take up in water, filter and wash, making the total volume about 400 cu.cm. Heat to boiling and add slowly a slight excess of hot 10 per cent $BaCl_2$ solution. Allow to stand over night, filter, wash, ignite, weigh the $BaSO_4$ and calculate to sulphur.

Specific Gravity

29. The specific gravity shall be the ratio of the weight of a given volume of the rubber, to the weight of an equal volume of water, both at 20 deg.cent. Cut strips of the largest applicable size from the conductor and use about 5 g. for the sample. Determine the specific gravity in the usual manner by means of a specific gravity bottle. Care must be taken that no air bubbles adhere to the sample.

Checks

30. Specific gravity determinations shall check within 0.01. The other duplicate determinations shall check within the following limits expressed as percentages of the original sample.

Determination	Check
Acetone Extract	0.10
Saponifiable Acetone Extract	0.10
Unsaponifiable Resins	0.10
Waxy Hydrocarbons	0.10
Free Sulphur	0.05
Chloroform Extract	0.10
Alcoholic Potash Extract	0.10
Fillers, free from sulphur	0.50
Total Sulphur	0.10

Interpretation

31. The *Rubber* shall be considered to be the difference between 100 and the sum of the Waxy Hydrocarbons, Total Sulphur and the Fillers (free from sulphur), expressed as percentages. If the Chloroform Extract is over 3.0 per cent of the rubber so calculated, subtract the excess from the Rubber. If the KOH extract is over 1.8 per cent of the Rubber, as first calculated, subtract this excess also from the Rubber.

Carbon and Red Lead

32. Heat about one g. of the sample with 30 cu.cm. conc. HNO_3 and 15 cu.cm. water. A black insoluble residue indicates the presence of carbon.

When the rubber is dissolved, in the fillers determination, the absence of any red particles indicates the absence of red lead. If red particles are present, dissolve another sample by the same method as the fillers (Section 26), filter the solution into a Gooch crucible and wash thoroughly. Remove the felt and residue to a distilling flask, add HCl, and distill over the chlorine liberated by the lead peroxide, absorbing the gas in a solution of KI and starch. Not more than 0.1 cu.cm. $\frac{N}{10}$ thiosulphate shall be required to titrate the iodine liberated.

Statement of Results

33. The results of the analysis shall be stated in the following form:

	Per cent
Acetone extract	
Saponifiable acetone extract	
Unsaponifiable resins	
Waxy Hydrocarbons	
Free sulphur	
Chloroform extract	
Alcoholic Potash extract	
Fillers free from sulphur	
Total sulphur	
Rubber	
Color of acetone extract (60 cu.cm. vol.)	
Fluorescence in acetone extract solution (present or absent)	
Hydrocarbons A (consistency and color)	
Hydrocarbons B (solid or liquid)	
Color of chloroform extract (60 cu.cm. vol.)	
Carbon (present or absent)	
Red Lead (present or absent)	
Specific Gravity	

Part III—Explanation of Procedure

General

1. The Committee felt the more acceptable solution of its problem of drawing up a procedure which would give the percentage of rubber present in a compound with a reasonable degree of accuracy, to be the perfection and amplification of the difference method rather than the development of a direct method, which if equally correct, might not inspire confidence because of the comparative novelty of its application to this purpose.

2. The most feasible means of limiting the kind of rubber, was considered to be the determination of the saponifiable and unsaponifiable resins. These are fairly constant characteristics of the resins of *Hevea* rubber, and of compounds made from the same. Other methods, such as the determination of the saponification number and the optical activity of the resins, were thought to be unpractical.

3. The method as developed is applicable to the analysis of any pure rubber compound containing only mineral matter with or without ceresine or paraffine wax, regardless of the kind or amount of rubber, and can

be used in conjunction with other specifications provided the limits are changed to correspond with the amount and kind of rubber desired, and due consideration is given to interfering mineral matter. When applied to a compound without ceresine or paraffine wax the unsaponifiable acetone extract is the unsaponifiable resins.

4. The method has been definitely described, to make it certain that experienced chemists may obtain concordant results. The interpretation has been rigidly defined, obviating any ambiguity as to the meaning that will be assumed, even though this sometimes appears to be arbitrary.

Sample

5. In order to obtain uniform results, the Committee has established by experiment that a definite method of sampling has to be adopted and that for all extractions the sample must be reduced in a prescribed manner to at least an approximately similar degree of fineness. For this reason the procedure specifies a definite type of grinder obtainable in two forms, and also specifies definite sieves.

Extraction Apparatus

6. The Committee has proved that the extraction apparatus used by different chemists must be of exactly the same form and the same size. It was also proven that small samples in the apparatus give the maximum results and that the rate of extraction is dependent upon the amount of solvent and its temperature as it passes through the sample. The apparatus finally adopted combines the advantages of several forms that were studied and together with simplicity of operation and adjustment to uniform conditions, gives practically complete extraction when used as specified. A number of other variations that might have a possible effect upon the amount of extract, were tried but found to be inappreciable.

Acetone Extraction

7. The extraction is made within 24 hours of the preparation of the sample, so obviating any appreciable oxidation. Two samples are extracted and united, so that a larger amount of extract may be obtained for the subsequent separations, and the extraction apparatus kept within a convenient size. Hot chloroform is used to facilitate the complete transference of the extract. The flasks are placed on their sides when drying, to hasten the emission of the solvent and thus reduce chance of volatilizing, through longer heating, some of the more volatile constituents of the extract. Drying in vacuo at room temperature, does not remove all the moisture if paraffine is present and such drying with heat or at 100 deg. cent. in an inert gas, presents no practical advantage over the method given.

Separation of the Acetone Extract

8. The method given was devloped so that all the desired constituents could be determined on one sample.

9. Emphasis is laid on thorough extraction of the unsaponifiable material and the retention of the flocculent material with the etherial solution. This latter material is not soluble in either ether or water, but it was proven that if such as was chloroform-soluble was included in the unsaponifiable material, the subsequent determination of the hydrocarbons would be more exact. A portion of this flocculent material is insoluble in chloroform.

10. The hydrocarbons are determined in two places, making an approximate separation between the solid and the liquid ones, if both are present. The first hydrocarbons (A) are those insoluble in the solvent at a low temperature. The presence of unsaponifiable resins in the solution prevents the more complete freezing out of the hydrocarbons, but the remainder is obtained after treatment of the resins with sulphuric acid. In this way, chance of loss through the action of the acid has been largely eliminated.

11. The method for free sulphur gives all the sulphur in the acetone extract with the exception of negligible amounts which may be in the unsaponifiable material. It was proven that the results agree with determinations made directly on other acetone extracts.

12. The saponifiable and unsaponifiable resins are obtained by difference.

Chloroform Extraction

13. The chloroform extraction should be made at once after the acetone extraction, or the sample put in a vacuum, so as to avoid the danger of an abnormally high extract. When the extract is dried as specified constant weight is obtained before any appreciable oxidation occurs. If bituminous substances are present, that portion which has not been extracted by the acetone, will be largely soluble in chloroform and can be readily distinguished by its color. The amount of extract is also affected by the presence of uncured rubber and rubber of low degree of polymerization. A properly cured *Hevea* compound will always give a little extract with chloroform, which varies somewhat with the method and conditions of cure.

Alcoholic Potash Extraction

14. The alcoholic potash extraction is the usual saponification process for obtaining the fatty acids of rubber substitutes. The total amount of such substitutes is not obtained, but if any appreciable amount is present, the value will exceed that of the limit allowed. When no substitutes are present, this determination always yields a small amount of extract from *Hevea* rubber.

Fillers

15. Since the rubber is determined by difference, it is necessary to determine the amount of fillers. Ashing the compound gives accurate results provided no volatile or decomposable fillers are included. This, however, cannot be assumed to be the case. The determination of fillers by using solvents to dissolve the rubber, has always presented a difficult problem and it is only after a great many experiments that the Committee can report a reasonably satisfactory method.

16. Many kinds and probably every class of rubber solvents were tried, with the result that some did not completely dissolve the rubber at low temperatures and ordinary atmospheric pressure; others appeared to dissolve the rubber, but formed a colloidal solution holding some of the fillers which could neither be filtered nor centrifuged clear of mineral matter, and the ones that did not present these difficulties consumed much time.

17. Terebene was found to be the solvent which would most completely dissolve the rubber and after continued heating would completely destroy the rubber in solution as such, and so break up the colloidal solution. Filtering out the mineral matter is then a comparatively simple

process. The treatment with terebene must be performed in the presence of air to break up the colloidal solution. A disadvantage of using terebene is the length of time required to obtain satisfactory solution. The speed is greatly hastened if at first xylol is used with the terebene. After decanting this solution, terebene is used alone. The rapidity of the action is also hastened by increasing the temperature. That specified gives reasonable speed without serious danger of carbonizing the rubber or of losing any of the fillers by decomposition.

18. It was proven that there is organic matter derived from the rubber, which is insoluble in the solvents and remains with the fillers. Without taking this into account, the fillers will appear high, and the rubber by difference, low. As this organic matter was proven to be largely proteid matter, and this was originally a part of the rubber, an allowance is made for it. This is the amount generally retained when the method is carried out as specified. It is possible, by centrifuging, to throw out of the solution a great deal more than this, and it is also possible to determine the approximate amount retained in each case, but the slight increase in accuracy does not justify the extra determination.

19. Most of the details of this procedure are self-evident, but it is probably worthy of note that the benzol solutions are filtered into a separate beaker, as otherwise the benzol is apt to precipitate, from the terebene solution, organic matter which may be mistaken for mineral matter or conceal mineral matter passing through the filter. The filtrates are ashed since traces of mineral matter are always found in them. Emphasis must be laid upon the necessity of conducting blanks on the solvents.

Sulphur in Fillers

20. The sulphur in fillers is determined in order to calculate the rubber by difference. It is carried out only on the fillers obtained on the filter paper, the sulphur in the ash from the filtrate and washings, being negligible.

Total Sulphur

21. Several methods for total sulphur were tried. The method given was found to yield accurate results.

Interpretation of Results

22. Emphasis is laid on the method of calculating the results. The saponifiable acetone extract and the unsaponifiable resins are considered to be parts of the rubber. The chloroform and alcoholic potash extracts, when within the limits specified, are also so considered. It has been explained that the proteid matter with the fillers has been allowed for, since it also is a part of the rubber. The fillers are calculated sulphur-free, so that the sulphur will not be subtracted twice. No allowance is made for the ash in the raw rubber as it is considered to be negligible. This method of calculation has to be adopted if the rubber found is to agree with that originally put into the compound.

Moisture

23. A determination of moisture is not given, as electrical tests will detect its presence if in excess. If electrical tests are required, the error introduced by the omission of this determination, is very small.

Note: With a procedure of this length it is impossible to explain every detail without undue elaboration and the Committee wishes to point out

that while to experienced chemists the procedure may seem overburdened by detail, yet every specified detail was found necessary in order that the conditions essential to accurate and consistent work might be reproduced by all chemists using the procedure. For this reason it is extremely important that all instructions be observed even if their significance is not perceived by the individual chemist. It will probably be found that even with the instructions properly observed, some experience will be needed to apply the method successfully.

PART IV—SPECIFICATION FOR 30 PER CENT HEVEA RUBBER COMPOUND

1. A 30 per cent fine *Para* or smoked first latex *Hevea* rubber compound with mineral base, shall be furnished. It shall contain only the following ingredients:

Rubber.
Sulphur.
Inorganic mineral matter.
Refined solid paraffine or ceresine.

2. It shall not contain either red lead or carbon.

3. The vulcanized compound shall conform to the following requirements, when tested by the procedure of the Joint Rubber Insulation Committee.

(a) Results to be expressed as percentages by weight of the whole sample:

	Maximum	Minimum
Rubber	33	30
Waxy hydrocarbons	4	..
Free sulphur	0.7	..

(b) Results to be taken between the limits given in proportion to the percentage by weight of rubber found:

Limits allowed for 30 per cent Rubber Compound.	Maximum	Minimum
Saponifiable acetone extract	1.35	0.55
Unsaponifiable resins	0.45	....
Chloroform extract	0.90	....
Alcoholic potash extract	0.55	....
Total sulphur (see note 2)	2.10	....
Specific gravity	....	1.75
Limits allowed for 33 per cent Rubber Compound.		
Saponifiable acetone extract	1.50	0.60
Unsaponifiable resins	0.50	....
Chloroform extract	1.00	....
Alcoholic potash extract	0.60	....
Total sulphur (see note 2)	2.30	....
Specific gravity	....	1.67

4. The acetone solution shall not fluoresce.

5. The acetone extract (60 cu.cm.) shall be not darker than a light straw color.

6. Hydrocarbons shall be solid, waxy and not darker than a light brown.

7. Chloroform extract (60 cu.cm.) shall be not darker than a straw color.

8. Failure to meet any requirement of this specification will be considered sufficient cause for rejection.

9. Contamination of the compound, such as by the use of impregnated tapes, will not excuse the manufacturer from conforming to this specification.

Note 1: This specification shall be supplemented by appropriate

clauses relating to tensile strength, elasticity, insulation resistance and dielectric strength.

Note 2: The limit on total sulphur may be omitted at the option of the purchaser. See Part V of Report.

Part V—Explanation of Specification

1. Experience has shown that compounds which upon analysis, show the characteristics of good *Hevea* rubber, may be relied upon to be more permanent than those made of rubber of other grades. It is not affirmed by the Committee that a compound which conforms with this specification, is necessarily permanent, or that a better compound cannot be made, but it is believed that enforcement of the specification will limit the use of inferior materials and that it will put the manufacturers more nearly upon an equality of endeavor, where they can use their experience to obtain the best results. Used in connection with the analytical procedure, the specification will enable purchasers to order a good compound and to ascertain with a greater certainty than heretofore, whether the material received, represents the compound specified.

2. The term *Hevea* applied to rubber means rubber from the *Hevea Brasiliensis* tree whether wild or cultivated and regardless of the locality in which it has been grown. *Para* rubber is *Hevea* rubber which has been shipped from the port of Para, Brazil, and comes in several grades. Smoked first latex *Hevea* rubber is a high grade of plantation rubber which is collected prime and consists entirely of rubber which has risen in the settling vats. It is coagulated chemically and smoked in order to give it a hard cure, which ensures the greatest durability. The rubber required by this specification should be *Hevea* rubber of good quality, such a *fine Para* or smoked first latex plantation rubber.

3. Carbon is excluded because it is considered, by some purchasers, to be deleterious.

4. Red lead is excluded because of the possibilities of its deleterious effects on the rubber.

5. Ozokerite is prohibited because the acetone extract obtainable from it interferes with the separation of the acetone extract obtainable from the rubber, thereby vitiating the assay of the rubber extract. This prohibition is unimportant to the manufacturers, as ceresine, which is permitted, is the essential constituent of ozokerite.

6. An upper limit is placed upon the rubber in order to prevent the attainment of electrical and mechanical strength by the use of an extra quantity of inferior rubber whose lasting qualities might not be satisfactory.

7. The hydrocarbons are limited owing to their tendency to separate from the compound and thus possibly cause porosity.

8. The free sulphur is limited because an excessive amount may be deleterious.

9. The maximum limit on the saponifiable acetone extract is to prevent the use of raw or reclaimed rubber with high saponifiable extract. The minimum limit assists in forcing the use of *Hevea* rubber, since it is characteristic of the acetone extract from *Hevea* rubber to be largely saponifiable.

10. The unsaponifiable resins are limited because a low proportion of unsaponifiable resins is characteristic of *Hevea* rubber. A high result might be due to the presence of reclaimed rubber.

11. The chloroform extract is limited, first to prevent the use of bituminous substances, and second, to limit depolymerized and undercured rubber.

12. The alcoholic potash extract is limited to prevent the use of saponifiable rubber substitutes.

13. The specific gravity is limited to reconcile the specification of ingredients by weight with the practise of purchasing material by volume.

14. Fluorescence of the acetone solution is prohibited as it indicates the presence of mineral oils.

15. The color of the acetone extracts is specified to conform with the normal color of the extract from *Hevea* rubber. A darker color indicates adulteration or an inferior grade of rubber.

16. The hydrocarbons are required to be solid in order to prevent the use of oils and paraffine of low melting point. The shade required is that obtained from paraffine wax or ceresine. If hydrocarbons B are liquid this would indicate reclaimed rubber softened with mineral oil, or a poor grade of paraffine.

17. The color of the chloroform extract is specified to conform with the color of dissolved gum in minute quantities. The presence of bituminous substances would be indicated by a brown or black color.

18. It would be desirable that the sulphur of vulcanization be limited to exclude reclaimed rubber, which contains the sulphur of its previous vulcanization, but the Committee has not yet developed an acceptable method for determining this quantity. It is, therefore, confronted with the choice of either placing a limit on the total sulphur or giving up the attempt to exclude shoddy by sulphur limitation. Option is therefore given to the purchaser to insert or omit the limit on total sulphur. Such insertion will at times exclude reclaimed rubber and the Committee believes it possible to make a suitable compound with this limitation. The Committee thinks that a sulphur limit positively excluding reclaimed rubber, would place too great a hardship, in other ways, on the manufacturers. Where the specification is used with no total sulphur limit, the use of many kinds of, or much, reclaimed rubber, will be guarded against by the limits of the various components of the acetone extract. When the limitation on total sulphur is omitted, sulphur-bearing fillers, which possess certain advantages, may be used.

19. This specification should be supplemented by appropriate elasticity and tensile strength tests, in order to add to the assurance that good rubber has been used and that the vulcanization process has been properly carried out; also by appropriate electric stress and resistance tests, to assure proper insulating qualities and homogeneity of structure. The exact values of the limits for these tests will depend upon the use to which the material is to be put.

JOINT RUBBER INSULATION COMMITTEE

Mr. C. R. Boggs,	Mr. J. P. Millwood,
Mr. W. S. Clark,	Mr. P. Poetschke,
Mr. W. B. Geiser,	Mr. H. B. Rodman,
Mr. J. B. Tuttle,	Mr. E. L. Willson,

Mr. W. A. Del Mar, Sec'y.

Room 4849, Grand Central Terminal Bldg., New York.

October 1, 1913.

STANDARDIZATION RULES*

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

HISTORY OF THE STANDARDIZATION RULES

The first step taken by the Institute toward the standardization of electrical apparatus and methods was a topical discussion on "The Standardization of Generators, Motors and Transformers," which took place simultaneously in New York and Chicago on the evening of January 26, 1898. The discussion appears in the Institute TRANSACTIONS, Vol. XV, pages 3 to 32. The opinions expressed were generally favorable to the scheme of standardization of electrical apparatus, although some members feared that difficulties might arise. As a result of this discussion, a Committee on Standardization was appointed by the Council of the Institute, consisting of the following members:

FRANCIS B. CROCKER, *Chairman.*

CARY T. HUTCHINSON	CHARLES P. STEINMETZ
ARTHUR E. KENNELLY	LEWIS B. STILLWELL
JOHN W. LIEB, JR.	ELIHU THOMSON

After a careful consideration of the matter and consultation with the members of the Institute and interested parties generally, a "Report of the Committee on Standardization," was presented and accepted by the Institute, June 26, 1899. Those original rules appeared in the Institute TRANSACTIONS, Vol. XVI, pages 255 and 268.

As a result of changes and developments in the electric art, it was subsequently found necessary to revise the original report, this work being carried out by the following Committe on Standardization:

FRANCIS B. CROCKER, *Chairman.*

ARTHUR E. KENNELLY	CHARLES P. STEINMETZ
JOHN W. LIEB, JR.	LEWIS B. STILLWELL
C. O. MAILLOUX	ELIHU THOMSON

This revised report was adopted at the 19th Annual Convention at Great Barrington, Mass., on June 20, 1902, and appears in the Institute TRANSACTIONS, Vol. XIX, pages 1075 to 1092.

In consequence of still further change and development in electric l apparatus and methods, it was decided in September, 1905, that a second revision was needed, and the following Committee was appointed to do this work.

FRANCIS B. CROCKER, *Chairman.*
ARTHUR E. KENNELLY, *Secretary.*

HENRY S. CARHART	CHARLES F. SCOTT
JOHN W. LIEB, JR.	CHARLES P. STEINMETZ
C. O. MAILLOUX	HENRY G. STOTT
ROBERT B. OWENS	S. W. STRATTON

*NOTE: This edition of the Standardization Rules, which became effective July 1, 1915, is a revision of the edition of December 1, 1914.

This Committee held monthly meetings and carried on extensive correspondence with manufacturers, consulting and operating engineers and other interested parties, and as a result, presented its report at the 23d Annual Convention, held at Milwaukee, May 28–30, 1906. After considerable discussion the report was accepted and referred back to the Committee for amendment and rearrangement in form. It was then to be submitted to the Board of Directors for final adoption. In September, 1906, the following Standardization Committee was appointed:

FRANCIS B. CROCKER, *Chairman.*
ARTHUR E. KENNELLY, *Secretary.*

A. W. BERRESFORD	CHARLES F. SCOTT
DUGALD C. JACKSON	CHARLES P. STEINMETZ
C. O. MAILLOUX	HENRY G. STOTT
ROBERT B. OWENS	S. W. STRATTON

ELIHU THOMSON

This Committee held monthly meetings, also sub-committee meetings, and carefully referred the rules as a whole, and each part of them, to the members of the Institute. The rules were also entirely rearranged as to form, and put in shape to facilitate ready reference to them and enable future revisions to be made without breaking up the logical arrangement. Thus amended the rules were submitted to the Board of Directors and approved by it on June 21, 1907. The Board also directed that the rules should be presented, as accepted by the Board, at the Annual Convention held at Niagara Falls, June 24 to 27, 1907, which action was taken by President Sheldon on June 26, 1907. By the Constitution which went into effect on June 10, 1907, this Committee has been made a standing Committee with the title "Standards Committee," consisting of nine members.

On August 12, 1910, the Board of Directors increased the size of the committee from nine to twelve members; on October 14 from twelve to fourteen, and on March 10, 1911, from fourteen to sixteen. The committee thus constituted is given below.

COMFORT A. ADAMS, *Chairman.*
ARTHUR E. KENNELLY, *Secretary.*

H. W. BUCK	W. S. MOODY
GANO DUNN	R. A. PHILIP
H. W. FISHER	W. H. POWELL
H. B. GEAR	CHARLES ROBBINS
J. P. JACKSON	E. B. ROSA
W. L. MERRILL	CHARLES P. STEINMETZ
RALPH D. MERSHON	CALVERT TOWNLEY

This committee and several sub-committees held numerous meetings at which the general revision of the Standardization Rules of the Institute was considered. The complete Standardization Rules, as revised by this committee, were presented to and approved by the Board of Directors on June 27, 1911, at the Annual Convention held at Chicago, Ill.

During the following two years (1911-1913) the Standards Committee, somewhat modified and enlarged, undertook a radical revision of the Rules, particularly in connection with the important subject of Rating. In August 1913 the Committee was still further enlarged by the Board of Directors in order to permit of comprehensive sub-committees for the various parts of the work. The Committee thus constituted is given as follows:

A. E. KENNELLY, *Chairman.*
COMFORT A. ADAMS, *Secretary.*

SUB-COMMITTEE No. 1. ON RATING.

H. M. HOBART, *Chairman.*

JAMES BURKE	W. H. POWELL
W. C. L. EGLIN	CHARLES ROBBINS
B. G. LAMME	C. F. SCOTT
W. A. LAYMAN	JAMES M. SMITH
W. L. MERRILL	CHARLES P. STEINMETZ
W. S. MOODY	J. FRANKLIN STEVENS

PHILIP TORCHIO

SUB-COMMITTEE No. 2. ON TELEGRAPH AND TELEPHONE STANDARDS.

F. B. JEWETT, *Chairman.*

H. W. FISHER	R. H. MARRIOTT
F. F. FOWLE	J. H. MORECROFT

J. M. SMITH

SUB-COMMITTEE No. 3. ON RAILWAY STANDARDS.

W. A. DEL MAR, *Chairman.*

F. W. CARTER*	WILLIAM MCCLELLAN
HUGH HAZELTON*	HAROLD PENDER
E. R. HILL*	MARTIN SCHREIBER*
H. M. HOBART	N. W. STORER*

SUB-COMMITTEE No. 4. ON NOMENCLATURE AND SYMBOLS

COMFORT A. ADAMS, *Chairman.*

LOUIS BELL	H. PENDER
DUGALD C. JACKSON	E. B. ROSA
M. G. LLOYD	A. S. MCALLISTER

R. H. MARRIOTT

SUB-COMMITTEE No. 5. ON WIRES AND CABLES.

H. W. FISHER, *Chairman.*

WALLACE CLARK	E. B. ROSA
W. A. DEL MAR	C. E. SKINNER
W. C. L. EGLIN	S. W. STRATTON

SUB-COMMITTEE NO. 6. ON RATING AND TESTING OF CONTROL APPARATUS.

L. T. ROBINSON, *Chairman.*

MORTON ARENDT	C. H. SHARP
R. A. CARLE	P. H. THOMAS

PHILIP TORCHIO

Sub-committee No. 1 had representation from the National Electric Light Association (Messrs. L. L. Elden, G. L. Knight, J. E. Kearns, and E. P. Dillon), from the Association of Edison Illuminating Companies (Mr. P. Torchio) and from the Electric Power Club (Messrs. James Burke and J. M. Smith).

Sub-committee No. 3, through Messrs. Schreiber and Del Mar, respectively, worked in collaboration with the Committees of the American Electric Railway Engineering Association, and the Association of Railway Electrical Engineers.

*Sub-committee No. 3 was a joint subcommittee of the Standards Committee and of the Railway Committee. The members opposite whose names occurs an asterisk, represented the latter committee.

The following members, although not appointed on the Standards Committee, have materially contributed to its work and have attended its meetings:

Carl J. Fechheimer, E. D. Priest, R. B. Williamson, K. A. Pauly, L. F. Blume, C. Renshaw, G. H. Hill, C. J. Hixson.

The radical revision begun in 1911 was completed by this Committee and approved by the Board of Directors at a special meeting held on July 10, 1914, subject to editorial revision by the Committee, and to go into force on Dec. 1, 1914.

The Committee of 1914-1915 which carried out the editorial revision, found it impossible to complete the work satisfactorily by Dec. 1st. The edition of July 1st, 1915, approved by the Board of Directors at its meeting of June 30, 1915, thus represents substantially the completion and clarification of the previous radical revision, although it includes a number of important additions. This Committee was constituted as follows:

A. E. KENNELLY, Chairman, Harvard University Cambridge, Mass.
C. A. ADAMS, Secretary, Harvard University, Cambridge, Mass.

JAMES BURKE, Erie, Pa.
W. A. DEL MAR, New York,
H. W. FISHER, Perth Amboy, N. J.
G. L. KNIGHT, Brooklyn, N. Y.
H. M. HOBART, Schenectady, N. Y.
P. B. JEWETT, New York.
P. JUNKERSFELD, Chicago, Ill.
W. L. MERRILL, Schenectady, N. Y.
W. H. POWELL, Milwaukee, Wis.
CHARLES ROBBINS, East Pittsburgh, Pa.
L. T. ROBINSON, Schenectady, N. Y.
E. B. ROSA, Washington, D. C.
C. E. SKINNER, East Pittsburgh, Pa.
J. M. SMITH, New York.
H. G. STOTT, New York.
P. H. THOMAS, New York.

NOTE.

The Standards Committee takes this occasion to draw the attention of the membership to the value of suggestions based upon experience gained in the application of the Rules to general practise.

Any suggestions looking toward improvement in the Rules should be communicated to the Secretary of the Institute, for the guidance of the Standards Committee in the preparation of future editions.

TABLE OF CONTENTS

Preface ..... Page 1792
Definitions ..... Section 1
Symbols and Abbreviations 90
Classification of Machinery 100
Standards for Electrical Machinery 250
Kinds of Rating 281
Heating and Temperature 300
Temperature Limits 375
Additional Requirements 375
Wave-Form 405
Efficiency and Losses 420
Determination or Approximation of Losses 450
Tests of Dielectric Strength of Machinery 480
Insulation Resistance of Machinery 550
Regulation 560
Transformer Connections 600
Information on the Rating Plate of a Machine 620
Standards for Wires and Cables 635
Standards for Switches and Other Circuit-Control Apparatus 720
Standards for Electric Railways 760
Standards for Illumination and Photometry 850
Standards for Telephony and Telegraphy 910
Appendix I, Standards for Radio Communication 1000
Appendix II, Additional Standards for Railway Motors 1100
Appendix III, Bibliography of Literature Relating to Electrical Engineering Standardization ..... page 1883
Index of Contents ..... " 1884

LIST OF TABLES

		Page
I.	Symbols and Abbreviations	1798
II.	Temperature Coefficients of Copper Resistance	1815
III.	Permissible Temperatures and Temperature Rises for Insulating Materials	1817
IV.	Permissible Hottest-Spot Temperatures and Limiting Observable Temperature Rises in other than Water Cooled Machinery	1818
V.	Classification of Losses in Machinery	1823
VI.	Brush-Contact Drop	1826
VII.	Needle-Gap Spark-over Voltages	1832
VIII.	Spherometer Specifications	1833
IX.	Sphere-Gap Spark-over Voltages	1834
X.	Air-Density Correction Factor for Sphere-Gaps	1835
XI.	Insulation Resistance of Machinery	1836
XII.	Standard Stranding of Cables	1848
XIII.	Proposed Standard Stranding of Flexible Cables	1849
XIV.	Recommended Test Kilovolts Corresponding to Operating Kilovolts	1851
XV.	Operating Temperatures of Railway Motors	1861
XVI.	Stand-Test Temperature Rises of Railway Motors	1861
XVII.	Core Loss in D-C. Railway Motors at Various Loads	1863
XVIII.	Losses in Axle Bearings and Single Reduction Gearing of Railway Motors	1863
XIX.	Photometric Units and Abbreviations	1870
XX.	Approximate Losses in D-C. Railway Motors	1880

PREFACE

In framing these rules, the chief purpose has been to define the terms and conditions which characterize the rating and behavior of electrical apparatus, with special reference to the conditions of acceptance tests.

It has not been the purpose of the rules to standardize the dimensions or details of construction of any apparatus, lest the progress of design and production should be hampered.

DEFINITIONS

NOTE. The following definitions are intended to be practically descriptive, rather than scientifically rigid.

CURRENT, E.M.F. and POWER.

(The definitions of currents given below apply also, in most cases, to electromotive force, potential difference, magnetic flux, etc.)

1 **Direct Current.** A unidirectional current. As ordinarily used, the term designates a practically non-pulsating current.

2 **Pulsating Current.** A current which pulsates regularly in magnitude. As ordinarily employed, the term refers to unidirectional current.

3 **Continuous Current.** A practically non-pulsating direct current.

4 **Alternating Current.** A current which alternates regularly in direction. Unless distinctly otherwise specified, the term "alternating current" refers to a periodic current with successive half waves of the same shape and area.

5 **Oscillating Current.** A periodic current whose frequency is determined by the constants of the circuit or circuits.

6 **Cycle.** One complete set of positive and negative values of an alternating current.

7 **Electrical Degree.** The 360th part of a cycle.

8 **Period.** The time required for the current to pass through one cycle.

9 **Frequency.** The number of cycles or periods per second. The product of 2π by the frequency is called the *angular velocity* of the current.

10 **Root-Mean-Square** or **Effective Value.** The square root of the mean of the squares of the instantaneous values for one complete cycle. It is usually abbreviated r.m.s. Unless otherwise specified, the numerical value of an alternating current refers to its r.m.s. value. The r.m.s. value of a sinusoidal wave is equal to its maximum, or crest value, divided by $\sqrt{2}$. The word "virtual" is sometimes used in place of r.m.s., particularly in Great Britain.

11 **Wave-Form** or **Wave-Shape.** The shape of the curve obtained when the instantaneous values of an alternating current are plotted against time in rectangular co-ordinates. The distance along the time axis corresponding to one complete cycle of values is taken as 2π radians, or 360 degrees. Two alternating quantities are said to have the same wave-form when their ordinates of corresponding phase (see § 13) bear a constant ratio to each other. The wave-shape, as thus understood, is therefore independent of the frequency of the current and of the scale to which the curve is represented.

12 **Simple Alternating** or **Sinusoidal Current.** One whose wave-shape is sinusoidal.

Alternating-current calculations are commonly based upon the assumption of sinusoidal currents and voltages.

13 **Phase.** The distance, usually in angular measure, of the base of any ordinate of an alternating wave from any chosen point on the time axis, is called the phase of this ordinate with respect to this point. In the case of a sinusoidal alternating quantity, the phase at any instant may be represented by the corresponding position of a line or *vector* revolving about a point with such an angular velocity ($\omega = 2\pi f$), that its projection at each instant upon a convenient reference line is proportional to the value of the quantity at that instant.

14 **Non-Sinusoidal Quantities.** Quantities that cannot be represented by vectors of constant length in a plane. The following definitions of phase, active component, reactive component, etc., are not in general applicable thereto. Certain "equivalent" values, as defined below, may, however, be used in many instances, for the purpose of approximate representation and calculation.

15 **Crest-Factor or Peak-Factor.** The ratio of the crest or maximum value to the r.m.s. value. The crest factor of a sine-wave is $\sqrt{2}$.

16 **Form Factor.** The ratio of the r.m.s. to the algebraic mean ordinate taken over a half-cycle beginning with the zero value. If the wave passes through zero more than twice during a single cycle, that zero shall be taken which gives the largest algebraic mean for the succeeding half-cycle. The form factor of a sine-wave is 1.11.

17 **The Distortion Factor of a wave.** The ratio of the r.m.s. value of the first derivative of the wave with respect to time, to the r.m.s. value of the first derivative of the equivalent sine wave.

18 **Equivalent Sine Wave.** A sine wave which has the same frequency and the same r.m.s. value as the actual wave.

*19 **Phase Difference: Lead and Lag.** When corresponding cyclic values of two sinusoidal alternating quantities of the same frequency occur at different instants, the two quantities are said to differ in phase by the angle between their nearest corresponding values; *e.g.*, the phase angle between their nearest ascending zeros or between their nearest positive maxima. That quantity whose maximum value occurs first in time is said to lead the other, and the latter is said to lag behind the former.

*20 **Counter-Clockwise Convention.** It is recommended that in any vector diagram, the leading vector be drawn counter-clockwise with respect to the lagging vector,† as in the accompanying diagram, where OI represents the vector of a current in a simple alternating-current circuit, lagging behind the vector OE of impressed e.m.f.

*21 **The Active or In-Phase Component** of the current in a circuit is that component which is in phase with the voltage across the circuit; similarly the active component of the voltage across a circuit is that component which is in phase with the current. The use of the term *energy component* for this quantity is disapproved.

*Note: Definitions 19, 20, 21, 22, 23, 24, 25 refer strictly only to cases where the voltage and current are both sinusoidal (see §11 and 12).

†See Publication 12 of the International Electrotechnical Commission (Report of Turin Meeting, Sept. 1911, p. 78).

*22 **Reactive or Quadrature Component of the current in a circuit.** That component which is in quadrature with the voltage across the circuit; similarly, the reactive component of the voltage across the circuit is that component which is in quadrature with the current. The use of the term *wattless component* for this quantity is disapproved.

*23 **Reactive Factor.** The sine of the angular phase difference between voltage and current; *i. e.*, the ratio of the reactive current or voltage to the total current or voltage.

*24 **Reactive Volt-Amperes.** The product of the reactive component of the voltage by the total current, or of the reactive component of the current by the total voltage.

*25 **Non-Inductive Load and Inductive Load.** A *non-inductive* load is a load in which the current is in phase with the voltage across the load. An *inductive* load is a load in which the current lags behind the voltage across the load. A *condensive* or *anti-inductive* load is one in which the current leads the voltage across the load.

26 **Power in an Alternating-Current Circuit.** The average value of the products of the coincident instantaneous values of the current and voltage for a complete cycle, as indicated by a wattmeter.

27 **Volt-Amperes or Apparent Power.** The product of the r.m.s. value of the voltage across a circuit by the r.m.s. value of the current in the circuit. This is ordinarily expressed in kv-a.

28 **Power Factor.** The ratio of the power (cyclic average as defined in §26) to the volt-amperes. In the case of sinusoidal current and voltage, the power factor is equal to the cosine of their difference in phase.

29 **Equivalent Phase Difference.** When the current and e.m.f. in a given circuit are non-sinusoidal, it is customary, for purposes of calculation, to take as the "equivalent" phase difference, the angle whose cosine is the power factor (see §28) of the circuit. There are cases, however, where this equivalent phase difference is misleading, since the presence of harmonics in the voltage wave, current wave, or in both, may reduce the power factor without producing a corresponding displacement of the two wave forms with respect to each other; *e.g.*, the case of an a-c. arc. In such cases, the components of the equivalent sine waves, the equivalent reactive factor and the equivalent reactive volt-amperes may have no physical significance.

30 **Single-Phase.** A term characterizing a circuit energized by a single alternating e.m.f. Such a circuit is usually supplied through two wires. The currents in these two wires, counted positively outwards from the source, differ in phase by 180 degrees or a half-cycle.

31 **Three-Phase.** A term characterizing the combination of three circuits energized by alternating e.m.f.'s. which differ in phase by one-third of a cycle; *i.e.*, 120 degrees.

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*Note: Definitions 19, 20, 21, 22, 23, 24, 25 refer strictly only to cases where the voltage and current are both sinusoidal (see §11 and 12).

32 **Quarter-Phase, also called Two-Phase.** A term characterizing the combination of two circuits energized by alternating e.m.f's. which differ in phase by a quarter of a cycle; *i.e.*, 90 degrees.

33 **Six-Phase.** A term characterizing the combination of six circuits energized by alternating e.m.f's. which differ in phase by one sixth of a cycle; *i.e.*, 60 degrees.

34 **Polyphase.** A general term applied to any system of more than a single phase. This term is ordinarily applied to symmetrical systems.

Per Cent Drop.

50 In electrical machinery, the ratio of the **internal resistance drop** to the terminal voltage, expressed in per cent, is called the "*per cent resistance drop.*"

51 Similarly the ratio of the **internal reactance drop** to the terminal voltage, expressed in per cent, is called the "*per cent reactance drop.*"

52 Similarly the ratio of the **internal impedance drop** to the terminal voltage, expressed in per cent, is called the "*per cent impedance drop.*"

Unless otherwise specified, these per cent drops shall be referred to rated load and rated power factor.

53 **In the case of transformers,** the per cent drop will be the sum of the primary drop (reduced to secondary turns) and the secondary drop, in per cent of secondary terminal voltage.

54 **In the case of induction motors,** it is advantageous to express the drops in per cent of the internally induced e.m.f.

55 **The Load Factor of a machine, plant or system.** The ratio of the average power to the maximum power during a certain period of time. The average power is taken over a certain period of time, such as a day, a month, or a year, and the maximum is taken as the average over a short interval of the maximum load within that period.

In each case, the interval of maximum load and the period over which the average is taken should be definitely specified, such as a "half-hour monthly" load-factor. The proper interval and period are usually dependent upon local conditions and upon the purpose for which the load factor is to be used.

56 **Plant Factor.** The ratio of the average load to the rated capacity of the power plant, *i.e.*, to the aggregate ratings of the generators.

57 **The Demand of an installation or system.** The load which it puts on the source of supply, as measured at the receiving terminals. The demand may be as specified, contracted for, or used. It may be expressed either in kilowatts, kilovolt-amperes, amperes or other suitable units.

58 **The Maximum Demand of an installation or system.** Its greatest demand, as measured not instantaneously but averaged over a suitable and specified interval, such as a "five-minute maximum demand."

59 **Demand Factor.** The ratio of the maximum demand of any system or part of a system, to the total connected load of the system, or of the part of system, under consideration.

60 **Diversity Factor.** The ratio of the sum of the maximum power demands of the subdivisions of any system or parts of a system to the maximum demand of the whole system or of the part of the system under consideration, measured at the point of supply.

61 **Connected Load.** The combined continuous rating of all the receiving apparatus on consumers' premises, connected to the system or part of the system under consideration.

62 **The Saturation Factor of a machine.** The ratio of a small percentage increase in field excitation to the corresponding percentage increase in voltage thereby produced. Unless otherwise specified, the saturation factor of a machine refers to the no-load excitation required at normal rated speed and voltage. It is determined from measurements of saturation made on open circuit at rated speed.

63 **The Percentage Saturation** of a machine at any excitation may be found from its saturation curve of generated voltage as ordinates, against excitation as abscissas, by drawing a tangent to the curve at the ordinate corresponding to the assigned excitation, and extending the tangent to intercept the axis of ordinates drawn through the origin. The ratio of the intercept on this axis to the ordinate at the assigned excitation, when expressed in percentage, is the percentage of saturation and is independent of the scales selected for excitation and voltage. This ratio, as a fraction, is equal to the reciprocal of the saturation-factor at the same excitation, deducted from unity; or, if f be the saturation factor and p the percentage of saturation,

$$p = 100\left(1 - \frac{1}{f}\right)$$

64 **Magnetic Degree.** The 360th part of the angle subtended, at the axis of a machine, by a pair of its field poles. One **mechanical degree** is thus equal to as many magnetic degrees as there are pairs of poles in the machine.

65 **The Variation in Prime Movers** which do not give an absolutely uniform rate of rotation or speed, as in reciprocating steam engines, is the maximum angular displacement in position of the revolving member expressed in degrees, from the position it would occupy with uniform rotation, and with one revolution taken as 360 degrees.

66 **The Variation in Alternators** or alternating-current circuits in general, is the maximum angular displacement, expressed in electrical degrees, (one cycle = 360 deg.) of corresponding ordinates of the voltage wave and of a wave of absolutely constant frequency equal to the average frequency of the alternator or circuit in question, and may be due to the variation of the prime mover.

67 **Relations of Variations in Prime Mover and Alternator.** If p is the number of pairs of poles, the variation of an alternator is p times the variation of its prime mover, if direct-connected, and pn times the variation of the prime mover if rigidly connected thereto in such a manner that the angular speed of the alternator is n times that of the prime mover.

68 **The Pulsation in Prime Movers, or in the alternator connected thereto.** The ratio of the difference between the maximum and minimum velocities in an engine-cycle to the average velocity.

80 **Capacity.** The two different senses in which this word is used sometimes lead to ambiguity. It is therefore recommended that whenever such ambiguity is likely to arise, the descriptive term *power capacity* or *current capacity* be used, when referring to the power or current which a device can safely carry, and that the term "*Capacitance*" be used when referring to the electrostatic capacity of a device.

81 **Resistor.** A device, heretofore commonly known as a resistance, used for the operation, protection, or control of a circuit or circuits. See **§ 740.**

82 **Reactor.** A coil, winding or conductor, heretofore commonly known as a reactance coil or choke coil, possessing inductance, the reactance of which is used for the operation, protection or control of a circuit or circuits. See also **§ 214** and **736.**

83 **Efficiency.** The efficiency of an electrical machine or apparatus is the ratio of its useful output to its total input.

TABLE I.

90 **Symbols and Abbreviations.**

Name of Quantity.	Symbol for the Quantity.	Unit.	Abbreviation for the Unit.
Electromotive force, abbreviated e.m.f.	E, e	volt	....
Potential difference, abbreviated p.d.	V, v or E, e	"	....
Voltage	E, e or V, v	"	....
Current	I, i	ampere	....
Quantity of electricity	Q, q	coulomb, ampere-hour	....
Power	P, p	watt	....
Electrostatic flux	Ψ	....	....
Electrostatic flux density	D	....	....
Electrostatic field intensity	F		
Magnetic flux	Φ, φ	maxwell*	....
Magnetic flux density	$B, \mathfrak{B}$	gauss*	....
Magnetic field intensity	$H, \mathfrak{H}$	gilbert per centimeter or gauss†	gilbert per cm. ....
Magnetomotive force, abbreviated m.m.f.	$\mathfrak{F}$	gilbert*	....
Intensity of magnetization	J	....	....
Susceptibility	$\kappa = J/H$	....	....
Permeability	$\mu = B/H$	....	....

* An additional unit for m. m. f. is the "ampere-turn", for flux the "line", for magnetic flux-density "maxwells per sq. in."

† The gauss is provisionally accepted for the present as the name of both the unit of field intensity and flux density, on the assumption that permeability is a simple numeric.

Resistance	R, r	ohm	....
Reactance	X, x	"	....
Impedance	Z, z	"	....
Conductance	g	mho	....
Susceptance	b	"	....
Admittance	Y, y	"	....
Resistivity	ρ	* ohm-centimeter	ohm-cm.
Conductivity	γ	*mho per centimeter	mho per cm.
Dielectric constant	ϵ or k	....	....
Reluctance	$\mathcal{R}$	....	....
Capacitance (Electrostatic capacity)	C	farad	....
Inductance (or coefficient of self induction)	L	henry	....
Mutual Inductance (or coefficient of mutual induction)	M	henry	....
Phase displacement	θ, φ	degree or radian	°
Frequency	f	cycle per second	~
Angular velocity	ω	radian per second	....
Velocity of rotation	n	revolution per second	rev. per sec.
Number of conductors or turns	N	convolution or turns of wire	
Temperature	T, t, θ	degree centigrade	°C
Energy, in general	U or W	joule, watt-hour	....
Mechanical work	W or A	joule, watt-hour	....
Efficiency	η	per cent	....
Length	l	centimeter	cm.
Mass	m	gram	g.
Time	t	second	sec.
Acceleration due to gravity	g	centimeter per second per second	cm. per sec. per sec.
Standard acceleration due to gravity (at about 45 deg. latitude and sea level) equals 980.665†	g_o	centimeter per second per second	cm. per sec. per sec.

**Note.* The numerical values of these quantities are *ohms resistance* and *mhos conductance* between two opposite faces of a cm. cube of the material in question, but the correct names are as given, not ohms and mhos per cm. cube, as commonly stated.

†This has been the accepted standard value for many years and was formerly considered to correspond accurately to 45° Latitude and sea level. Later researches, however, have shown that the most reliable value for 45° and sea-level is slightly different; but this does not affect the standard value given above.

91 E_m, I_m and P_m should be used for maximum cyclic values, e, i and p for instantaneous values, E and I for r.m.s. values (see **§10**) and P for the average value of the power, or the active power. These distinctions are not necessary in dealing with continuous-current circuits. In print, vector quantities should be represented by bold-face capitals.

CLASSIFICATION OF MACHINERY.

100 The machinery under consideration in these rules may be classified in various ways, these various classifications overlapping or interlocking in considerable degree. Briefly, they are Direct-Current or Alternating-Current, Rotating or Stationary. Under Rotating Apparatus there are two principal classifications: *First*, according to the function of the machines; Motors, Generators, Boosters, Motor-Generators, Dynamotors, Double-Current Generators, Converters and Phase Modifiers; *Second*, according to the type of construction or principle of operation; Commutating, Synchronous, Induction, Unipolar, Rectifying. Obviously, some of these machines could be rationally included in either classification, *e.g.*, Motor-Generators and Rectifying Machines.

In the following, self-evident definitions have for the most part, been omitted.

ROTATING MACHINES.

FUNCTIONAL CLASSIFICATION OF ROTATING MACHINES.

101 **Generator.** A machine which transforms mechanical power into electrical power.

102 **Motor.** A machine which transforms electrical power into mechanical power.

103 **Booster.** A generator inserted in series in a circuit to change its voltage. It may be driven by an electric motor (in which case it is termed a motor-booster) or otherwise.

104 **Motor-Generator Set.** A transforming device consisting of a motor mechanically coupled to one or more generators.

105 **Dynamotor.** A transforming device combining both motor and generator action in one magnetic field, either with two armatures, or with one armature having two separate windings and independent commutators.

106 **A Direct-Current Compensator** or **Balancer** comprises two or more similar direct-current machines (usually with shunt or compound excitation) directly coupled to each other and connected in series across the outer conductors of a multiple-wire system of distribution, for the purpose of maintaining the potentials of the intermediate wires of the system, which are connected to the junction points between the machines.

107 **A Double-Current Generator** supplies both direct and alternating currents from the same armature-winding.

108 **A Converter** is a machine employing mechanical rotation in changing electrical energy from one form into another. There are several types of converters as follow:

109 **A Direct-Current Converter** converts from a direct current to a direct current, usually with a change of voltage. Such a machine may be either a motor-generator set or a dynamotor.

110 **A Synchronous Converter** (sometimes called a Rotary Converter) converts from an alternating to a direct current, or vice-versa. It is a synchronous machine with a single closed-coil armature winding, a commutator and slip rings.

111 **A Cascade Converter,** also called a **Motor Converter,** is a combination of an induction motor with a synchronous converter, the secondary circuit of the former feeding directly into the armature of the latter; *i.e.*, it is a synchronous converter concatenated with an induction motor.

112 **A Frequency Converter** converts the power of an alternating-current system from one frequency to another, with or without a change in the number of phases, or in the voltage.

113 **A Rotary Phase-Converter** converts from an alternating-current system of one or more phases to an alternating-current system of a different number of phases, but of the same frequency.

114 **A Phase-Modifier,** also called *a Phase-Advancer*, is a machine which supplies reactive volt-amperes; *e.g.* to an induction motor, or to the system to which it is connected. Phase modifiers may be either synchronous or asynchronous.

115 **A Synchronous Phase-Modifier,** sometimes called a Synchronous Condenser, is a synchronous motor, running either idle or with load, the field excitation of which may be varied so as to modify the power-factor of the system, or through such modification to influence the load voltage. The function of a Synchronous Phase-Modifier is to supply reactive volt-amperes to the system with which it is connected.

CONSTRUCTIONAL CLASSIFICATION OF ROTATING MACHINES

Commutating Machines

130 **Direct-Current Commutating Machines** comprise a magnetic field of constant polarity, an armature, and a commutator connected therewith. These include: Direct-Current Generators; Direct-Current Motors; Direct-Current Boosters; Direct-Current Motor-Generator Sets and Dynamotors; Direct-Current Compensators or Balancers; and Arc Machines.

131 **Alternating-Current Commutating Machines*** comprise a magnetic field of alternating polarity, an armature, and commutator connected therewith.

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*Definitions of a-c. commutator-motors have not yet been agreed upon. The differences of opinion are fundamental and relate to the whole system to be employed in naming the numerous types. One example of this difference is in connection with the definition of the term "Repulsion-Motor", some desiring to extend its use to cover all a.c. commutator motors with short-circuited brushes, and others to substitute more systematic names for the various species of short-circuited brush motors.

132 **Synchronous Commutating Machines** include synchronous converters, cascade-converters, and double-current generators.

133 **Synchronous Machines** Comprise a constant magnetic field and an armature receiving or delivering alternating-currents in synchronism with the motion of the machine; *i.e.*, having a frequency strictly proportional to the speed of the machine. They may be sub-divided as follow:

134 **An Alternator** is a synchronous alternating-current generator, either single-phase or polyphase.

135 **A Polyphase Alternator** is a polyphase synchronous alternating-current generator, as distinguished from **a singlephase alternator.**

136 **An Inductor Alternator is an Alternator** in which both field and armature windings are stationary, and in which masses of iron or inductors, by moving past the coils, alter the magnetic flux through them. It may be either singlephase or polyphase.

137 **A Synchronous Motor** is a machine structurally identical with an alternator, but operated as a motor.

138 **Induction Machines** include apparatus wherein primary and secondary windings rotate with respect to each other; *i.e.*, induction motors, induction generators, certain types of frequency converters and certain types of rotary phase-converters.

139 **An Induction Motor** is an alternating-current motor, either singlephase or polyphase, comprising independent primary and secondary windings, one of which, usually the secondary, is on the rotating member. The secondary winding receives power from the primary by electromagnetic induction.

140 **An Induction Generator** is a machine structurally identical with an induction motor, but driven above synchronous speed as an alternating-current generator.

141 **Unipolar or Acyclic Machines** are direct-current machines, in which the voltage generated in the active conductors maintains the same direction with respect to those conductors.

SPEED CLASSIFICATION OF MOTORS.

150 **Motors** may, for convenience, be classified with reference to their speed characteristics as follow:

151 **Constant-Speed Motors,** whose speed is either constant or does not materially vary; such as synchronous motors, induction motors with small slip, and ordinary direct-current shunt motors.

152 **Multispeed Motors** two-speed, three-speed, etc.), which can be operated at any one of several distinct speeds, these speeds being practically independent of the load; such as motors with two armature windings, or induction motors in which the number of poles is changed by external means.

153 **Adjustable-Speed Motors,** in which the speed can be varied gradually over a considerable range, but when once adjusted remains practically unaffected by the load, such as shunt motors designed for a considerable range of speed variation.

154 **Varying-Speed Motors,** or motors in which the speed varies with the load, ordinarily decreasing when the load increases; such as series motors, compound-wound motors, and series-shunt motors. As a sub-class of varying-speed motors, may be cited, **adjustable varying-speed motors,** or motors in which the speed can be varied over a considerable range at any given load, but when once adjusted, varies with the load; such as compound-wound motors arranged for adjustment of speed by varying the strength of the shunt field.

CLASSIFICATION OF ROTATING MACHINES RELATIVE TO THE DEGREE OF ENCLOSURE OR PROTECTION

160 The following types are recognized:

Open
Protected
Semi-enclosed
Enclosed
Separately ventilated
Water-cooled
Self-ventilated
Drip-proof
Moisture-resisting
Submersible
Explosion-proof
Explosion-proof slip-ring enclosure

161 **An "open" machine** is of either the pedestal-bearing or end-bracket type where there is no restriction to ventilation, other than that necessitated by good mechanical construction.

162 **A "protected" machine** is one in which the armature, field coils, and other live parts are protected mechanically from accidental or careless contact, while free ventilation is not materially obstructed.

163 **A "semi-enclosed" machine** is one in which the ventilating openings in the frame are protected with wire screen, expanded metal, or other suitable perforated covers, having apertures not exceeding ¼ of a square inch (3.2 sq. cm.) in area.

164 **An "enclosed" machine** is so completely enclosed by integral or auxiliary covers as to prevent a circulation of air between the inside and outside of its case, but not sufficiently to be termed air-tight.

165 A **"separately ventilated" machine** has its ventilating air supplied by an independent fan or blower external to the machine.

166 A **"water-cooled" machine** is one which mainly depends on water circulation for the removal of its heat.

167 A **"self-ventilated" machine** differs from a separately ventilated machine only in having its ventilating air circulated by a fan, blower, or centrifugal device integral with the machine.

If the heated air expelled from the machine is conveyed away through a pipe attached to the machine, this should be so stated.

168 A **"drip-proof" machine** is one so protected as to exclude falling moisture or dirt. A "drip proof" machine may be either "open" or "semi-enclosed", if it is provided with suitable protection integral with the machine, or so enclosed as to exclude effectively falling solid or liquid material.

169 A **moisture-resisting machine** is one in which all parts are treated with moisture-resisting material. Such a machine shall be capable of operating continuously or intermittently in a very humid atmosphere, such as in mines, evaporating rooms, etc.

170 A **"submersible" machine** is a machine capable of withstanding complete submersion, in fresh water or sea water, as may be specified, for four hours without injury.

171 An **"explosion-proof" machine** is a machine in which the enclosing case can withstand, without injury, any explosion of gas that may occur within it, and will not transmit the flame to any inflammable gas outside it.

172 An induction motor in which the slip rings and brushes alone are included within an explosion-proof case should not be described as an explosion-proof machine, but as a machine "with **explosion-proof slip-ring enclosure.**"

STATIONARY INDUCTION APPARATUS

200 **Stationary Induction Apparatus** changes electric energy to electric energy, through the medium of magnetic energy, without mechanical motion. It comprises several forms, distinguished as follow:

201 **Transformers**, in which the primary and secondary windings are ordinarily insulated one from another.

202 The terms **"high-voltage"** and **"low-voltage"** are used to distinguish the winding having the greater from that having the lesser number of turns. The terms **"primary"** and **"secondary"** serve to distinguish the windings in regard to energy flow, the primary being that which receives the energy from the supply circuit, and the secondary that which receives the energy by induction from the primary.

203 The **rated current of a constant-potential transformer** is that secondary current which, multiplied by the rated-load secondary voltage, gives the kv-a. rated output. That is, a transformer of given kv-a. rating must be capable of delivering the rated output at rated secondary voltage, while the primary impressed voltage is increased to whatever value is necessary to give rated secondary voltage.

The **Rated Primary Voltage** of a constant-potential transformer is the rated secondary voltage multiplied by the turn ratio.

204 The **ratio of a transformer,** unless otherwise specified, shall be the ratio of the number of turns in the high-voltage winding to that in the low-voltage winding; *i.e.*, the "turn-ratio."

205 The **voltage ratio** of a transformer is the ratio of the r.m.s. primary terminal voltage to the r.m.s. secondary terminal voltage, under specified conditions of load.

206 The "**current ratio**" of a current-transformer is the ratio of r.m.s. primary current to r.m.s. secondary current, under specified conditions of load.

207 The "**marked ratio**" of an instrument transformer is the ratio which the apparatus is designed to give under average conditions of use. When a precise ratio is required, it is necessary to specify the voltage, frequency, load and power factor of the load.

208 **Volt-Ampere Ratio of Transformers.**

The volt-ampere ratio, which should not be confused with real efficiency, is the ratio of the volt-ampere output to the volt-ampere input of a transformer, at any given power factor.

209 **Auto-transformers** have a part of their turns common to both primary and secondary circuits.

210 **Voltage Regulators** have turns in shunt and turns in series with the circuit, so arranged that the voltage ratio of the transformation or the phase relation between the circuit-voltages is variable at will. They are of the following three classes:

211 **Contact Voltage Regulators,** in which the number of turns in one or both of the coils is adjustable.

212 **Induction Voltage Regulators,** in which the relative positions of the primary and secondary coils are adjustable.

213 **Magneto Voltage Regulators,** in which the direction of the magnetic flux with respect to the coils is adjustable.

214 **Reactors,** heretofore commonly called **Reactance-Coils,** also called **Choke Coils**; a form of stationary induction apparatus used to supply reactance or to produce phase displacement. See also **§82** and **736.**

INSTRUMENTS

225 **An Ammeter** is an instrument for measuring current, indicating in amperes.

226 **A Voltmeter** is an instrument for measuring difference of potential, indicating in volts.

227 **A Crest Voltage Meter** is a voltmeter designed to indicate either the crest; *i.e.*, the maximum value, of an alternating voltage, or the r.m.s. value of the sinusoidal voltage having the same crest value.

288 **A Wattmeter** is an instrument for measuring electrical power, indicating in watts.

229 **Recording Ammeters, Voltmeters, Wattmeters, etc.,** are instruments which record graphically upon a time-chart the values of the quantities they measure.

230 **A Watt-hour Meter** is an instrument for registering watt-hours. This term is to be preferred to the term "integrating wattmeter."

231 **A Line-Drop Voltmeter Compensator** is a device used in connection with a voltmeter, which causes the latter to indicate the voltage at some distant point of the circuit.

232 **A Synchroscope, sometimes called a Synchronism Indicator,** is a device which, in addition to indicating synchronism, shows whether the incoming machine is fast or slow.

STANDARDS FOR ELECTRICAL MACHINERY

250 *The expressions "machinery" and "machines" are here employed in a general sense, in order to obviate the constant repetition of the words "machinery or induction apparatus."*

251 *All temperatures are to be understood as centigrade.*

252 *The expression "capacity" is to be understood as indicating "capability", except where specifically qualified, as, for instance, in the case of allusions to electrostatic capacity, i. e., capacitance.*

253 *Wherever special rules are given for any particular type of machinery or apparatus (such as switches, railway motors, railway substation machinery, etc., these special rules shall be followed, notwithstanding any apparent conflict with the provisions of the more general sections. In the absence of special rules on any particular point, the general rules on this point shall be followed.*

260 **Objects of Standardization.** To ensure satisfactory results, electrical machinery should be specified to conform to the Institute Standardization Rules, in order that it shall comply, in operation, with approved limitations in the following respects, so far as they are applicable.

Operating temperature
Mechanical strength
Commutation
Dielectric strength
Insulation resistance
Efficiency
Power factor
Wave shape
Regulation

261 **Capacity or Available Output of an Electrical Machine.** So far as relates to the purposes of these Standardization Rules, the Institute defines the Capacity of an Electrical Machine as the load which it is capable of carrying for a specified time (or continuously), without exceeding in any respect the limitations herein set forth.

Except where otherwise specified, the capacity of an electrical machine shall be expressed in terms of its available *output*. For exceptions see **§277** and **802.**

262 **Rating of an Electrical Machine.** Capacity should be distinguished from Rating. The Rating of a machine is the output marked on the Rating Plate, and shall be based on, but shall not exceed, the maximum* load which can be taken from the machine under prescribed conditions of test. This is also called the rated output.

*The term "maximum load" does not refer to loads applied solely for mechanical, commutation, or similar tests.

263 **The Principle upon which Machine Ratings** are based, so far as relates to thermal characteristics, is that the rated load, applied continuously or for a stated period, shall produce a temperature rise which, superimposed upon a standard ambient temperature, will not exceed the maximum safe operating temperature of the insulation.

264 **A. I. E. E. and I. E. C. Ratings.** When the prescribed conditions of test are those of the A. I. E. E. Standardization Rules, the rating of the machine is the Institute Rating. (See **§620**). When the prescribed conditions of the test are those of the I. E. C.† Rules, the rating of the machine is the I. E. C. rating. A machine so rated in either case may bear a distinctive sign upon its rating plate.

265 **Standard Temperature and Barometric Pressure for Institute Rating.** The Institute Rating of a machine shall be its capacity when operating with a cooling medium of the ambient temperature of reference (40° for air or 25° for water, see **§305** and **309**) and with barometric conditions within the range given in **§308**. See **§320**.

266 **The Temperatures Rises Specified in these Rules** apply to all ambient temperatures up to and including 40°C.

267 **Any Machinery Destined for Use with Higher Ambient** temperatures or cooling mediums, and also any machinery for operation at altitudes for which no provision is made in **§308**, should be the subject of special guarantee by the manufacturer. The methods of test and performance set forth in these Rules will, however, afford guidance in such cases.

UNITS IN WHICH RATING SHALL BE EXPRESSED

274 The rating of **Direct-Current Generators,** shall be expressed in kilowatts (kw.) available at the terminals.

275 The rating of **Alternators** and **Transformers,** shall be expressed in kilovolt-amperes (kv-a.) available at the terminals, at a specified power factor. The corresponding kilowatts should also preferably be stated.

276 It is strongly recommended that the **rating of motors** shall be expressed in kilowatts* (kw.) available at the shaft. (An ex-

†I. E. C. stands for "International Electrotechnical Commission." This rating has not yet been established.

*Since the input of machinery of this class is measured in electrical units and since the output has a definite relation to the input, it is logical and desirable to measure the delivered power in the same units as are employed for the received power. Therefore, the output of motors should be expressed in kilowatts instead of in horse power. However, on account of the hitherto prevailing practice of expressing mechanical output in horse power, it is recommended that for machinery of this class the rating should, for the present, be expressed both in kilowatts and in horse power; as follows:

kw.————approx. equiv. h.p.————

The horse power rating of a motor may for practical purposes, be taken as 4/3 of the kilowatt rating.

In order to lay stress upon the preferred future basis, it is desirable that on Rating Plates, the Rating in kilowatts shall be shown in larger and more prominent characters than the rating in horse power.

ception to this rule is made in the case of Railway motors, which, for some purposes, are also rated by their *input*, see **§802.**)

277 **Auxiliary machinery,** such as regulators, resistors, reactors, balancer sets, stationary and synchronous condensers, etc., shall have their ratings appropriately expressed. It is essential to specify also the voltage (and frequency, if a-c.,), of the circuits on which the machinery may appropriately be used.

KINDS OF RATING

There are various kinds of rating such as:

281 **Continuous Rating.** A machine rated for continuous service; shall be able to operate continuously at its rated output, without exceeding any of the limitations referred to in **§260.**

282 **Short-Time Rating.** A machine rated for short-time service; (*i.e.* service including runs alternating with stoppages of sufficient duration to ensure substantial cooling), shall be able to operate at its rated output during a limited period, to be specified in each case, without exceeding any of the limitations referred to in **§260**. Such a rating is a **short-time rating.**

283 **Nominal Ratings.** For railway motors, and sometimes for railway-substation machinery, certain nominal ratings are employed. See **800** and **§765.**

284 **Duty-Cycle Operation.** Many machines are operated on a cycle of duty which repeats itself with more or less regularity. For purposes of rating, either a continuous or a short-time equivalent load, may be selected, which shall simulate as nearly as possible the thermal conditions of the actual duty cycle.

285 **Standard durations of equivalent tests** shall be for machines operating under specified duty-cycles as follow:

5 minutes
10 "
30 "
60 "
120 "
and continuous.

Of these the first five are short-time ratings, selected as being thermally equivalent to the specified duty cycle.

When, for example, a short-time rating of 10 minutes duration is adopted, and the thermally equivalent load is 25 kw. for that period, then such a machine shall be stated to have a 10-minute rating of 25 kw.

286 In every case the equivalent short-time test shall commence only when the windings and other parts of the machine are **within 5°C of the ambient temperature** at the time of starting the test.

287 In the absence of any specification as to the kind of rating, the continuous rating shall be understood.*

*An exception is made in the case of motors for railway service, where in the absence of of any specification as to the kind of rating, the "nominal rating" as defined in **§319** and **410** shall be understood.

288 Machines marked in accordance with **§264** shall be understood to have a continuous rating, unless otherwise marked in accordance with **§285**.

HEATING AND TEMPERATURE

300 **Temperature Limitations of the Capacity of Electrical Machinery.** The capacity, so far as relates to temperature, is usually limited by the maximum temperature at which the materials in the machine, especially those employed for insulation, may be operated for long periods without deterioration. When the safe limits are exceeded, deterioration is rapid. The insulating material becomes permanently damaged by excessive temperature, the damage increasing with the length of time that the excessive temperature is maintained, and with the amount of excess temperature, until finally the insulation breaks down.

301 The result of operating at temperatures in excess of the safe limit is to shorten the life of the insulating material. This shortening of life is, in certain special cases, warranted, when necessary for obtaining some other desirable result, as, for example, in some instances of railway and other motors for propelling vehicles, in providing greater power within a limited space. See **§804**. Further instances may also be noted in the cases of contactors, controllers, induction-starters, arc-lamp-magnet windings, etc., designed and constructed for operation at relatively high temperatures.

302 There does not appear to be any advantage in operating at lower temperatures than the safe limits, so far as the life of the insulation is concerned. Insulation may break down from various causes, and when these breakdowns occur, it is not usually due to the temperature at which the insulation has been operated, provided the safe limits have not been exceeded.

303 **The Ambient Temperature** is the temperature of the fluid or fluids which, coming into contact with the heated parts of a machine, carries off its heat convectively.

304 **The cooling fluid may** either be led to the machine through ducts, or through pipes, or merely surround the machine freely. In the former case the ambient temperature is to be measured at the intake of the machine itself. In the latter case see **§314**.

305 **Ambient Temperature of Reference for Air.** The standard ambient temperature of reference, when the cooling medium is air, shall be 40°C.

306 The permissible rises in temperature given in column 2 of table III in **§376** have been calculated on the basis of the standard ambient temperature of reference, by subtracting 40° from the highest temperatures permissible, which are given in column 1 of the same table.

307 A machine may be tested at any convenient ambient temperature, but whatever be the value of this ambient temperature, the

permissible rises of temperature must not exceed those given in column **2** of the table in **§376.**

308 **Altitude.** Increased altitude has the effect of increasing the temperature rise of some types of machinery. In the absence of information in regard to the height above sea level at which the machine is intended to work in ordinary service, this height is assumed not to exceed 1000 meters (3300 feet.) For machinery operating at an altitude of 1000 meters or less, a test at any altitude less than 1000 meters is satisfactory, and no correction shall be applied to the observed temperatures. Machines intended for operation at higher altitudes shall be regarded as special. See **§267.** It is recommended that when a machine is intended for service at altitudes above 1000 meters (3300 ft.) the permissible temperature rise at sea level, until more nearly accurate information is available, shall be reduced by 1 per cent for each 100 meters (330 ft.) by which the altitude exceeds 1000 meters. Water cooled oil transformers are exempt from this reduction.

309 **Ambient Temperature of Reference for Water-Cooled Machinery.** For water-cooled machinery, the standard temperature of reference for incoming cooling water shall be 25° C, measured at the intake of the machine.

310 **In the testing of water-cooled transformers,** it is not necessary to take into account the surrounding-air temperature, except where the cooling effect of the air is 15 per cent or more of the total cooling effect, referred to the standard ambient temperature of reference of 25°C. for water and 40°C. for air. When the effect of the cooling air is 15 per cent. or more of the total, the temperature of the cooling water should be maintained within 5°C. of the surrounding air. Where this is impractical, the ambient temperature should be determined from the change in the resistance of the windings, using a disconnected transformer, supplied with the normal amount of cooling water, until the temperature of the windings has become constant.

311 **In the case of rotating machines,** cooled by forced draught, a conventional weighted mean shall be employed, a weight of four being given to the temperature of the circulating air supplied through ducts (see **§304**), and a weight of one to the surrounding room air. **In the case of air-cooled transformers,** see "exception" **§321.**

312 **Machines Cooled by Other Means.** For machines cooled by other means, special rules are necessary.

313 **Outdoor Machinery Exposed to Sun's Rays.** Outdoor machinery not protected from the sun's rays at times of heavy load, must receive special consideration.

314 **Measurement of the Ambient Temperature During Tests of Machinery.** The ambient temperature is to be measured by means of several thermometers placed at different points around and half-way up the machine, at a distance of 1 to 2 meters (3 to 6 feet), and protected from drafts, and abnormal heat radiation, preferably as in **§316.**

315 The value to be adopted for the ambient temperature during a test, is the mean of the readings of the thermometers (placed as above), taken at equal intervals of time during the last quarter of the duration of the test.

316 In order to avoid **errors due to the time lag** between the temperature of large machines and the variations in the ambient air, all reasonable precautions must be taken to reduce these variations and the errors arising therefrom. Thus, the thermometer for determining the ambient temperature shall be immersed in a suitable liquid, such as oil, in a suitable heavy metal cup. This can be made to respond to various rates of change, by proportioning the amount of oil to the metal in the containing cup. A convenient form for such an oil-cup consists of a massive metal cylinder, with a hole drilled partly through it. This hole is filled with oil and the thermometer is placed therein with its bulb well immersed. The larger the machine under test, the larger should be the metal cylinder employed as an oil-cup in the determination of the ambient temperature. The smallest size of oil cup employed in any case shall consist of a metal cylinder 25 mm. in diameter and 50 mm. high (1 in. in diameter and 2 in high).

317 **Thermometers used for taking temperatures of Machinery** shall be covered by felt pads 3 mm. ($\frac{1}{8}$ inch) thick and 4 x 5 cm. wide ($1\frac{1}{2}''$x $2''$), cemented on; oil putty may be used for stationary and small apparatus.

318 **In Transformer Testing,** and sometimes in testing other machines, it may be desirable to avoid errors due to time lag in temperature changes, by employing an idle unit of the same size and subjected to the same conditions of cooling as the unit under test, for obtaining the ambient temperature as described in **§310.**

319 Where **machines are partly below the floor line** in pits, the temperature of the rotor shall be referred to a weighted mean of the pit and room temperatures, the weight of each being based on the relative proportions of the rotor in and above the pit. Parts of the stator constantly in the pit shall be referred to the ambient temperature in the pit.

320 **Correction for the Deviation of the Ambient Temperature of the Cooling Medium, at the Time of the Heat Test, from the Standard Ambient Temperature of Reference.** Numerous experiments have shown that deviation of the temperature of the cooling medium from that of the standard of reference, at the time of the heat run, has a negligible effect upon the temperature rise of the apparatus; therefore, no correction shall be applied for this deviation. It is, however, desirable that tests should be conducted at ambient temperatures not lower than 20°C.

321 *Exception*—**A Correction shall be applied** to the observed temperature rise of the windings of *Air-blast transformers*, due to difference in resistance, when the temperature of the ingoing cooling air differs from that of the standard of reference. This correction

shall be the ratio of the inferred absolute ambient temperature of reference to the inferred absolute temperature of the ingoing cooling air, *i. e.* the ratio $274.5/(234.5 + t)$; where t is the ingoing cooling-air temperature.

Thus, a cooling-air room temperature of 30°C. would correspond to an inferred absolute temperature of 264.5° on the scale of copper resistivity, and the correction to 40°C. (274.5° inferred absolute temperature) would be 274.5 / 264.5 = 1.04, making the correction factor 1.04; so that an observed temperature rise of say 50°C. at the testing ambient temperature of 30°C. would be corrected to 50 × 1.04 = 52°C. this being the temperature rise which would have occurred had the test been made with the standard ingoing cooling-air temperature of 40°C.

322 **Duration of Temperature Test of Machine for Continuous Service.** The temperature test shall be continued until sufficient evidence is available to show that the maximum temperature and temperature rise would not exceed the requirements of the rules, if the test were prolonged until a steady final temperature was reached.

323 **Duration of Temperature Test of Machine with a Short-Time Rating.** The duration of the temperature test of a machine with a short-time rating shall be the time required by the rating. (See **§285** and **286**).

324 **Duration of Temperature Test for Machine having more than One Rating.** The duration of the temperature test for a machine with more than one rating shall be the time required by that rating which produces the greatest temperature rise. In cases where this cannot be determined beforehand, the machine shall be tested separately under each rating.

325 **Temperature Measurements during Heat Run.** Temperature measurements, when possible, shall be taken during operation, as well as when the machine is stopped. The highest figures thus obtained shall be adopted. In order to abridge the long heating period, in the case of large machines, reasonable overloads of current, during the preliminary period, are suggested for them.

TEMPERATURE MEASUREMENTS

340 **The Actual Temperatures attained** in the different parts of a machine, and not the rises in temperature, affect the life of the insulation of the machine. (See **§300** to **302**).

341 **The Temperatures in the Different Parts of a Machine** which it would be desirable to ascertain, are the maximum temperatures reached in those parts.

342 **Whatever may be the Ambient Temperature** when the machine is in service, the limits of the maximum observable temperature and of temperature rise specified in the rules should not be exceeded in service; for, if the maximum temperature be exceeded, the insulation may be endangered, and if the rise be exceeded, the excess load may lead to injury, by exceeding limits other than those of

temperature; such as commutation, stalling load and mechanical strength.

343 As it is Usually Impossible to Determine the Maximum Temperature attained in insulated windings, it is convenient to apply a correction to the observable temperature, so as to approximate the difference between the actual maximum temperature and the observable temperature by the method used. This correction, or margin of security, is provided to cover the errors due to fallibility in the location of the measuring devices, as well as inherent inaccuracies in measurement and methods.

344 In Determining the Temperature of Different Parts of a Machine three methods as provided. The appropriate method for any particular case is set forth below.

345 Method No 1. Thermometer Method.

This method consists in the determination of the temperature, by mercury or alcohol thermometers, by resistance thermometers, or by thermocouples, any of these instruments being applied to the hottest accessible part of the *completed* machine, as distinguished from the thermocouples or resistance coils embedded in the machine as described under Method No. 3.

346 When Method No. 1 is Used, the hottest-spot temperature for windings shall be estimated by adding a hottest-spot correction of 15°C to the highest temperature observed, in order to allow for the practical impossibility of locating any of the thermometers at the hottest spot.

347 *Exception.* When the thermometers are applied directly to the surfaces of bare windings, such as an edgewise strip conductor, or a cast copper winding, a hottest-spot correction of 5°C., instead of 15°C, shall be made. For commutators, collector rings, bare metallic surfaces not forming part of a winding, or for oil in which apparatus is immersed, no correction is to be applied.

348 Method No. 2. Resistance Method.

This method consists in the measurement of the temperature of windings by their increase in resistance, corrected* to the instant of shut-down when necessary. In the application of this method, careful thermometer measurements must also be made, whenever practicable without disassembling the machine†, in order to increase the probability of revealing the highest observable temperature. Which-

*Whenever a sufficient time has elapsed between the instant of shut-down and the time of the final temperature measurement to permit the temperature to fall, suitable corrections shall be applied, so as to obtain as nearly as practicable the temperature at the instant of shut-down. This can sometimes be approximately effected by plotting a curve, with temperature readings as ordinates and times as abscissas, and extrapolating back to the instant of shut-down. In other instances, acceptable correction factors can be applied.

In cases where successive measurements show *increasing* temperatures after shut-down, the highest value shall be taken.

†As one of the few instances in which the thermometer check cannot be applied in Method No. 2, the rotor of a turbo-alternator may be cited.

ever measurement yields the higher temperature, that temperature shall be taken as the "highest observable" temperature and a hot-test-spot correction of 10°C added thereto.

349 **The Temperature Coefficient of Copper** shall be deduced from the formula $1/(234.5 + t)$. Thus, at an initial temperature $t = 40°C.$, the temperature co-efficient of increase in resistance per degree centigrade rise, is $1/(274.5) = 0.00364$. The following table, deduced from the formula, is given for convenience of reference.

TABLE II.

Temperature Coefficients of Copper Resistance.

Temperature of the winding, in degrees C. at which the initial resistance is measured.	Increase in resistance of copper per °C., per ohm of initial resistance.
0	0.00 427
5	0.00 418
10	0.00 409
15	0.00 401
20	0.00 393
25	0.00 385
30	0.00 378
35	0.00 371
40	0.00 364

350 **In Coils of Low Resistance,** where the joints and connections form a considerable part of the total resistance, the measurement of temperature by the resistance method shall not be used.

351 **The Temperature of the Windings of Transformers** is always to be ascertained by Method 2. In the case of air-blast transformers, it is especially important to place thermometers on the coils near the air outlet.

352* **Method No. 3. Embedded Temperature-Detector Method.**

This method consists in the use of thermo-couples or resistance temperature detectors, located as nearly as possible at the estimated hottest spot. When method No. 3 is used, it shall, when required, be checked by method No. 2; the hottest spot shall then be taken to be the highest value by either method, the required correction factors (**§348** and **§356**) being applied in each case.

353 **By Building into the Machine** suitably placed temperature detectors, a temperature not much less than that of the hottest spot will probably be disclosed. When these devices are adopted for such

temperature determinations, a liberal number shall be employed, and all reasonable efforts, consistent with safety, shall be made to locate them at the various places where the highest temperatures are likely to occur.

354 **Temperature-Detectors** should be placed in at least two sets of locations. One of these should be between a coil-side* and the core, and one between the top and bottom coil-sides where two coil-sides per slot are used. Where only one coil-side per slot is used, one set of detectors shall be placed between coil-side and core, and one set between coil-side and wedge.

355 Method No. 3 should be applied to all stators of machines with cores having a width of 50 cm. (20 in.) and over. It should also be applied to all machines of 5000 volts and over, if of over 500 kv-a., regardless of core width. This method is not required for induction-regulators, which shall be tested as transformers.

356 **Correction Factor for Method No. 3.**—In the case of two-layer windings, with detectors between coil-sides, and between coil-side and core, add 5° C to the highest reading. In single-layer windings, with detectors between coil-side and core and between coil-side and wedge, add to the highest reading 10° C. plus 1° C. per 1000 volts above 5000 volts of terminal pressure.

TEMPERATURE LIMITS

375 Table III gives the limits for the hottest-spot temperatures of insulations. The permissible limits are indicated in column 1 of the Table. The limits of temperature rise permitted under rated-load conditions are given in column 2, and are found by subtracting 40° C. from the figures in column 1. Whatever be the ambient temperature at the time of the test, the rise of temperature must never exceed the limits in column 2 of the table. The highest temperatures, and temperature rises, attained in any machine at the output for which it is rated, must not exceed the values indicated in the Table and clauses following.

376 **Permissible Temperatures and Temperature Rises For Insulating Materials.** Table III (see next page) gives the highest temperatures and temperature rises to which various classes of insulating materials may be subjected, based on a standard ambient temperature of reference of 40°C.

377 NOTE. The Institute recognizes the ability of manufacturers to employ Class B insulation successfully at maximum temperatures of 150° C. and even higher. However, as sufficient data covering experience over a period of years at such temperatures are at present unavailable, the Institute adopts 125° C as a conservative limit for this class of insulation, and any increase above this figure should be the subject of special guarantee by the manufacturer.

*A coil-side is one of the two active sides of a coil.

TABLE III.

Permissible Temperatures and Temperature Rises for Insulating Materials.

Class	Description of Material	1 Maximum Temperature to which the material may be subjected	2 Maximum Temperature Rise
A.	Cotton, silk, paper and similar materials, when so treated or impregnated as to increase the thermal limit, or when permanently immersed in oil; also enamelled wire*	105°C	65°C
B.	Mica, asbestos and other materials capable of resisting high temperatures, in which any Class A. material or binder is used for structural purposes only, and may be destroyed without impairing the insulating or mechanical qualities of the insulation	125°C	85°C
C.	Fireproof and refractory materials, such as pure mica, porcelain, quartz, etc.....	No limits specified.	

*For cotton, silk, paper and similar materials, when neither impregnated nor immersed in oil, the highest temperatures and temperature rises shall be 10°C below the limits fixed for Class A, in Table III.

378 When a lower-temperature class material is comprised in a completed product to such an extent, or in such ways, that its subjection to the temperature limits allowed for the higher-temperature class material, with which it is associated, would affect the integrity of the insulation either mechanically or electrically, the permissible temperature shall be fixed at such a value as shall afford ample assurance that no part of the lower-temperature class material shall be subjected to temperatures higher than those approved by the Institute and set forth above.

379 **TABLE IV**

Permissible Hottest Spot Temperatures and Limiting Observable Temperature Rises in Other than Water-Cooled Machinery

		Class	A†	B
		Permissible Hottest-Spot Temperature....	105°	125°
METHOD I THERMOMETER ONLY See §345 to §347		Hottest Spot Correction.....	15°	15°
		Limiting Observable Temperature.....	90°	110°
		Limiting Observable Temperature Rise above 40°C.....	50°	70°
METHOD II RESISTANCE See §348		Hottest Spot Correction.....	10°	10°
		Limiting Observable Temperature.....	95°	115°
		Limiting Observable Temperature Rise above 40°C.....	55°	75°
METHOD III EMBEDDED TEMPERATURE DETECTORS See §352 to §356	Double-Layer Windings. For all Voltages	Hottest Spot Correction.....	5°	5°
		Limiting Observable Temperature.....	100°	120°
		Limiting Observable Temperature Rise above 40°C...	60°	80°
	Single-Layer Windings. For 5000 volts or less	Hottest Spot Correction.....	10°	10°
		Limiting Observable Temperature.....	95°	115°
		Limiting Observable Temperature Rise above 40°C...	55°	75°
	Single-Layer Windings. For more than 5000 Volts	Hottest Spot Correction	10° + (*E*—5)*	10° + (*E*—5)
		Limiting Observable Temperature.....	95° — (*E*—5)	115° — (*E*—5)
		Limiting Observable Temperature Rise above 40°C...	55° — (*E*—5)	75° — (*E*—5)

†For cotton, silk, paper and similar materials, when neither impreganted nor immersed in oil, the highest temperatures and temperature rise shall be 10°C. below the limits fixed for class A.

*In these formulas, *E* represents the rated pressure between terminals in kilovolts. Thus for a three-phase machine with single-layer winding, and with 11 kilovolts between terminals, the hottest-spot correction to be added to the maximum observable temperature will be 16°C.

Special Cases of Temperature limits.

385 **Temperature of Oil.** The oil in which apparatus is permanently immersed shall in no part have a temperature, observable by thermometer, in excess of 90°C.

386 **Water-Cooled Transformers.** In these the hottest-spot temperature shall not exceed 90°C.

387 **Railway Motor Temperature Limits,** see **§804** and **805**.

388 **Squirrel-Cage and Amortisseur Windings.** In many cases the insulation of such windings is largely for the purpose of making the conductors fit tightly in their slots, and the slightest effective insulation is ample. In other cases, there is practically no insulating material on the windings. Consequently, the temperature rise may be of any value such as will not occasion mechanical injury to the machine.

389 **Collector Rings.** The temperature of collector rings shall not be permitted to exceed the "hottest-spot" values set forth in **§376** and **379** for the insulations employed either in the collector rings themselves or in adjacent insulations whose life would be affected by the heat from the collector rings.

390 **Commutators.** The observable temperature shall in no case be permitted to exceed the values given in **§376** and **379** for the insulation employed, either in the commutator or in any insulation whose life would be affected by the heat of the commutator.

391 **Cores.** The temperature of those parts of the iron core in contact with insulating materials must not be such as to occasion in those insulating materials temperatures or temperature rises in excess of those set forth in **§376** and **379**.

392 **Other parts,** (such as brush-holders, brushes, bearings, pole-tips, cores, etc.) All parts of electrical machinery other than those whose temperature affects the temperature of the insulating material, may be operated at such temperatures as shall not be injurious in any respect.

METHODS OF LOADING TRANSFORMERS FOR TEMPERATURE TESTS

393 Whenever practicable, transformers should be tested under conditions that will give losses approximating as nearly as possible to those obtained under normal or specified load conditions, maintained for the required time (See **§322** to **324**). The maximum temperature rises measured during this test should be considered as the observable temperature rises for the given load.

An approved method of making these tests is the **"loading-back"** method. The principal variations of this method are—

394 **With duplicate single-phase transformers.**

Duplicate single-phase transformers may be tested in banks of two, with both primary and secondary windings connected in parallel. Normal magnetizing voltage should then be applied and the required current circulated from an auxiliary source. One transformer can be held under normal voltage and current conditions, while the other may be operating under slightly abnormal conditions.

395 With one three-phase transformer.

One three-phase transformer may be tested in a manner similar to (a), provided the primary and secondary windings are each connected in delta for the test. Normal three-phase magnetizing voltage should be applied and the required current circulated from an auxiliary single-phase source.

396 With three single-phase transformers.

Duplicate single-phase transformers may be tested in banks of three, in a manner similar to (b) by connecting both primary and secondary windings in delta, and applying normal three-phase magnetizing voltage and circulating the required current from an auxiliary single-phase source.

397 NOTE:— Among other methods that have a limited application and can be used only under special conditions may be mentioned—

(1) Applying dead load by means of some form of rheostat.

(2) Running alternately for certain short intervals of time on open circuit and then on short circuit, alternating in this way until the transformer reaches steady temperature. In this test, the voltage for the open-circuit interval and the current for the short-circuit interval shall be such as to give the same integrated core loss, and the same integrated copper loss, as in normal operation.

ADDITIONAL REQUIREMENTS

398 Short-Circuit Stresses.

The Institute recognizes the self-destructibility, both mechanical and thermal, of certain sizes and types of machines, when subjected to severe short-circuits, and recommends that ample protection be provided in such cases, external to the machine if necessary.

Over-Speeds.

399 All Types of Rotating Machines shall be so constructed that they will safely withstand an over-speed of 25 per cent, except in the case of steam turbines, which, when equipped with emergency governors, shall be constructed to withstand 20 per cent over-speed.

400 In the case of Series Motors, it is impracticable to specify percentage values for the guaranteed over-speed, on account of the varying service conditions.

401 Water-wheel Generators shall be constructed for the maximum runaway speed which can be attained by the combined unit.

Momentary Loads.

402 Continuously Rated Machines shall be required to carry momentary loads of 150 per cent of the amperes corresponding to the continuous rating, keeping the rheostat set for rated load excitation, (See **§281, 764** and **803.**) and commutating machinery shall commutate successfully under this condition. Successful commutation is such that neither brushes nor commutator are injured by the test. In the case of direct-connected generators, this clause is not to be interpreted as requiring the prime mover to drive the generator at this overload.

403 **Machines for duty-cycle operation** shall be rated according to their equivalent load, either on the short-time or continuous basis, but if intended for operation with widely fluctuating loads, shall commutate successfully under their specified operating conditions. See § **284, 285.**

404 **Stalling Torque of Motors**

Motors for continuous service shall, except when otherwise specified, be required to develop a running torque at least 175 per cent of that corresponding to the running torque at their rated load, without stalling.

Obviously, duty-cycle machines must carry their peak loads without stalling.

WAVE FORM

405 The **Sine Wave** shall be considered as standard, except where deviation therefrom is inherent in the operation of the system of which the machine forms a part.

406 **The deviation of wave form** from the sinusoidal is determined by superposing upon the actual wave, (as determined by oscillograph), the equivalent sine wave of equal length, in such a manner as to give the least difference, and then dividing the maximum difference between corresponding ordinates by the maximum value of the equivalent sine wave. A maximum deviation of the wave from sinusoidal shape not exceeding 10 per cent is permissible, except when otherwise specified.

EFFICIENCY AND LOSSES

420 **Machine Efficiency** is the ratio of the power delivered by the machine to the power received by it.

421 **Plant Efficiency** is the ratio of the energy delivered from the plant to the energy received by it in the a specified period of time.*

422 Two efficiencies are recognized, conventional efficiency and directly-measured efficiency. Unless otherwise specified, the conventional efficiency is to be employed.

423 **Conventional Efficiency** of machinery is the ratio of the output to the sum of the output and the losses; or of the input minus the losses to the input; when, in either case, conventional values are assigned to one or more of these losses. The need for assigning conventional values to certain losses, arises from the fact that some of the losses in electrical machinery are practicably indeterminable, and must, in many cases, either be approximated by an approved method of test or else values recommended by the Institute and designated "conventional" values shall be employed for them in arriving at the "conventional efficiency."

424 **Efficiencies based upon Conventional Losses** shall be specifically stated to be conventional efficiencies.

425 **Directly-Measured Efficiency.** Input and output determinations of efficiency may be made directly, measuring the output by brake,

*An exception should be noted in the case of the efficiency of storage batteries.

or equivalent, where applicable. Within the limits of practical application, the circulating-power method, sometimes described as the Hopkinson or "loading-back" method, may be used.

426 Values of the Indeterminate Losses may also be obtained by brake or other direct test, and used in estimating actual efficiencies of similar machines, by the separate-loss method.

427 Normal Conditions. The efficiency shall correspond to, or be corrected to, the normal conditions herein set forth, which shall be regarded as standard. These conditions include voltage, current, power-factor, frequency, wave-shape, speed, temperature, or such of them as may apply in each particular case.

428 Measurement of Efficiency. Electric power shall be measured at the terminals of the apparatus. In polyphase machines, sufficient measurements shall be made on all phases to avoid errors of unbalance.

429 Point at Which Mechanical Power Shall be Measured. Mechanical power delivered by machines, shall be measured at the pulley, gearing, or coupling, on the rotor shaft, thus excluding the loss of power in the belt or gear friction. See, however, an exception in §800.

430 The Efficiency of Alternating-Current machinery shall be measured when the current is in phase with the terminal voltage, unless otherwise specified, or unless a definite phase difference is inherent in the apparatus, as in induction machinery.

431 Efficiency of Alternating-Current Machinery in regard to Wave Shape. In determining the efficiency of alternating-current machinery, the sine wave is to be considered as standard, unless a different wave form is inherent in the operation of the system. See §405.

432 Temperature of Reference for Efficiency Determinations. The efficiency, at all loads, of all apparatus, shall be corrected to a reference temperature of 75°C.

433 The losses in constant-potential machinery, either of the stationary type, or of the constant-speed rotary type, are of two classes; namely, those which remain substantially constant at all loads, and those which vary with the load. The former include iron losses, windage and friction, also I^2R losses in any shunt windings. The latter include I^2R losses in series windings. The constant losses may be determined by measuring the power required to operate the machine at no load, deducting any series I^2R losses. The variable loss at any load may be computed from the measured resistance of the series windings and the given load current.

434 Stray Load Losses. The above simple method of determining the losses and hence the efficiency is only approximate, since the losses which are assumed to be constant do actually vary to some extent with the load, and also because the actual loss in the copper windings is sometimes appreciably greater than the calculated I^2R loss. The difference between the approximate losses, as above determined, and the actual losses, is termed the "stray load losses"*.

*In Table V, the stray load losses include f, h, j, k, l and m; but do not include increased core losses due to increased excitation for compensating internal drop under load.

These latter are due to distortions in electric or magnetic fluxes from their no-load distributions or values, brought about by the load current. They are usually only approximately measurable, or may be indeterminable.

TABLE V

Classification of Losses in Machinery

435 Losses in machinery may be classified as follows:

Accurately Measurable or Determinable	*Approximately Measurable or Determinable*	*Indeterminable*
a. No-Load Core Losses including eddy-current losses in conductors at no-load	*c.* Brush Friction Loss	*h.* Iron Loss due to flux distortion.
b. Load I^2R losses in windings No-Load I^2R " " "	*d.* Brush-Contact Loss	*i.* Eddy-Current losses in conductors due to transverse fluxes occasioned by the load currents.
	e. Losses due to windage and to bearing friction	*k.* Eddy-Current losses in conductors due to tooth saturation resulting from distortion of the main flux.
	f. Extra copper loss in transformer windings, due to stray fluxes caused by load currents	*l* Tooth-frequency losses due to flux distortion under load.
	g. Dielectric Losses.	*m.* Short-Circuit Loss of Commutation.

436 **Evaluation of Losses.** The larger individual losses are either accurately or approximately determinable, but certain of the indeterm nable losses reach values in various kinds of machinery which require that they should be taken into account.

Methods of measuring, approximating or allowing for these various losses are given below.

LOSSES TO BE TAKEN INTO ACCOUNT IN VARIOUS TYPES OF MACHINES

440 **Direct-Current Commutating Motors and Generators.**

No-load core losses. (Accurately Measurable or Determinable).

I^2R loss in all windings. (Acc. Meas. or Deter.)

Brush contact I^2R loss. (Approximately Meas. or Deter).

Unless otherwise specified, use the Institute Standard of 1 volt

for contact drop per brush; *i. e.*, 2 volts for total brush drop, for either carbon or graphite brushes. See **§454** and **819**.

Friction of bearings and windage. (Approx. Meas. or Deter.)

Rheostat losses, when present. (Acc. Meas. or Deter.)

Brush friction. (Approx. Meas. or Deter.)

All indeterminable load losses (including stray-load iron losses) which may be important, which vary with the design, and for which no satisfactory method of determination has been found, shall be included as zero per cent in estimating conventional efficiency.

441 Synchronous Motors and Generators.

No-load core losses. (Acc. Meas. or Deter.)

I^2R loss in all windings. (Acc. Meas. or Deter.) based upon rated kw. and power factor.

Stray load-losses. (Indeterminable.) In approximating these losses, the method described in **§458** shall be employed.

Friction of bearings and windage. (Approx. Meas. or Deter.)

Brush friction and brush-contact loss is negligible.

Rheostat losses, when present, corresponding to rated kw. and power factor. (Acc. Meas. or Deter.)

442 Induction Machines.

No-load core losses. (Acc. Meas. or Deter.)

I^2R losses in all windings. (Acc. Meas. or Deter.)

Stray load-losses. (Indeterminable.) In approximating these losses, the method described in **§459** shall be employed.

Brush friction when collector rings are present. (Approx. Meas. or Deter.)

Brush-contact loss. (Approximately Meas. or Deter.). Unless otherwise specified, use the Institute Standard of 1 volt for contact drop per brush, for either carbon or graphite brushes. See **§454**.

Friction of bearings and windage (Approx. Meas. or Deter.)

443 Commutating A-C. Machines

No-load core losses. (Acc. Meas. or Deter.)

I^2R losses in all windings. (Acc. Meas. or Deter.)

Brush friction. (Approx. Meas. or Deter.)

Brush-contact loss. (Approx. Meas. or Deter.) Unless otherwise specified, use the Institute Standard of 1 volt for contact drop per brush, for either carbon or graphite brushes. See **§454** and **819**.

Friction of bearings and windage. (Approx. Meas. or Deter.)

Short-Circuit loss of commutation. (Indeterminable.) Iron loss due to flux distortion. (Indeterminable.) Eddy-current losses due to fluxes varying with load and saturation. (Indeterminable.)	The Institute is not at this time prepared to make recommendations for approximating these losses.

444 Synchronous Converters.

No-load core losses. (Acc. Meas. or Deter.)

I^2R losses in all windings, based on rated kw. and power factor. (Approx. Meas. or Deter.) The I^2R losses in the armature winding shall be derived from those corresponding to its use as a direct-current generator, by using recognized factors.

Brush friction. (Approx. Meas. or Deter.)

Rheostat losses when present, corresponding to rated kw. and power factor. (Acc. Meas. or Deter.)

Brush-contact loss. (Approx. Meas. or Deter.) Unless otherwise specified, use the Institute Standard of 1 volt for contact drop per brush,—for either carbon or graphite brushes. See **§454.**

Short-circuit loss of commutation. (Indeterminable)
Iron loss due to flux distortion when present. (Indeterminable).
Eddy-current losses due to fluxes varying with load and saturation. (Indeterminable.)
} These losses, while usually of low magnitude, are erratic, and the Institute is not at this time prepared to make recommendations for approximating them.

Friction of bearings and windage. (Approx. Meas. or Deter.)

For the booster type of synchronous converter, where the booster forms an integral part of the unit, its losses shall be included in the total converter losses in estimating the efficiency.

445 Transformers.

No-load losses. These include the core loss and the I^2R loss due to the exciting current, (Acc. Meas. or Deter.) also the dielectric hysteresis loss in the insulation, (Approx. Meas. or Deter.) (See **§470.**)

I^2R losses in all windings. (Acc. Meas. or Deter.)

Stray load losses. (Approx. Meas. or Deter.). These include eddy-current losses in windings and core, due to fluxes varying with load. See **§471,** for the method of approximating these losses.

DETERMINATION OR APPROXIMATION OF LOSSES IN ROTATING MACHINERY

450 Bearing Friction and Windage may be determined as follows. Drive the machine from an independent motor, the output of which shall be suitably determined. The machine under test shall have its brushes removed and shall not be excited. This output represents the bearing friction and windage of the machine under test.

The bearing friction and windage of induction motors may be measured by running motors free at the lowest voltage at which they will rotate continuously at approximately rated speed; the

watts input, minus I^2R loss, under these conditions being taken as the friction and windage.

In the case of engine-type generators, the windage and bearing friction loss is ordinarily very small, amounting to a fraction of one per cent of the output. In these rules this loss is neglected owing to its small value and the difficulty of measuring it.

451 **Brush Friction of Commutator and Collector Rings.** Follow the test of **§450,** taking an additional reading with the brushes in contact with the commutator or collector rings. The difference between the output obtained in the test in **§450** and this output shall be taken as the brush friction. Note: The surfaces of the commutator and brushes should already be smooth and glazed from running when this test is made.

452 **No-Load Core Loss.** Follow the test in **§451** with an additional reading taken with the machine excited. The difference between the output value of **§451** and the output value of this reading shall be taken as the no-load core loss. This no-load core loss shall be taken with the machine so excited, as to produce rated terminal voltage.

The Core Loss of Induction Motors may be determined by measuring the watts input to the motor when running free at normal rated voltage and frequency, and subtracting therefrom the no-load copper loss and the bearing friction and windage.

453 **No-Load Core Loss at the Internal Voltage Corresponding to Rated Load.** This shall be taken as in **§452,** except that the machine shall be so excited as to produce at the terminals the voltage corresponding to the calculated internal voltage for the load and power factor under consideration. For synchronous machines, since no generally accepted method is available for obtaining the stator reactance, the internal voltage shall be determined by correcting the terminal voltage for only the resistance drop.

454 **The Brush-Contact I^2R Loss** depends largely upon the material of which the brush is composed. As indicating the range of variation the following table will be of interest:

TABLE VI.

Brush-Contact Drop.

Grade of Brush	Volts drop across one brush-contact. (Average of positive and negative brushes)
Hard Carbon	1.1
Soft Carbon	0.9
Graphite	0.5 to 0.8
Metal-Graphite types	0.15 to 0.5 (The former for largest proportion of metal)

One volt drop per brush shall be considered as the Institute Standard drop corresponding to the I^2R brush-contact loss, for car

bon and graphite brushes. Metal-graphite brushes shall be considered as special. See **§819**.

455 **Field-Rheostat Losses** shall be included in the generator losses where there is a field rheostat in series with the field magnets of the generator, even when the machine is separately excited.

456 **Ventilating Blower.** When a blower is supplied as part of a machine set, the power required to drive it shall be charged against the complete unit; but not against the machine alone.

457 **Losses in Other Auxiliary Apparatus.** Auxiliary apparatus, such as a separate exciter for a generator or motor, shall have its losses charged against the plant of which the generator and exciter are a part, and not against the generator. An exception should be noted in the case of turbo-generator sets with direct-connected exciters, in which case the losses in the exciter shall be charged against the generator. The actual energy of excitation and the field-rheostat losses, if any, (see **§455**) shall be charged against the generator.

458 **Stray Load-Losses in Synchronous Generators and Motors.** These include iron losses, and eddy-current losses in the copper, due to fluxes varying with load and also to saturation.

Stray load-losses are to be determined by operating the machine on short circuit and at rated-load current. This, after deducting the windage and friction and I^2R loss, gives the stray load-loss for polyphase generators and motors. These losses in single-phase machines are large; but the Institute is not yet prepared to specify a method for measuring them.

459 **Stray Load-Losses in Induction Machines.**

These include eddy-current losses in the stator copper, and other eddy-current losses due to fluxes varying with the load. In windings consisting of relatively small conductors, these eddy-current losses are usually negligible.

With rotor removed, and for a given stator current, measure the input the stator at different frequencies. Plot a curve of loss against frequency. At low frequencies, the loss becomes constant, indicating the I^2R value. The difference between this I^2R value and the total loss at normal frequency, shall be taken as the stray load-loss. This method is not accurate with induction motors in which the slots are entirely closed. In such machines these losses may be greater.

460 **Polyphase Induction-Motor Rotor I^2R Loss.** This should be determined from the slip, whenever the latter is accurately determinable, using the following equation:

$$\text{Rotor } I^2R \text{ loss} = \frac{\text{Output} \times \text{slip}}{1 - \text{slip}}$$

In large slip-ring motors, in which the slip cannot be directly measured by loading, the rotor I^2R loss shall be determined by direct

resistance measurement; the rotor full-load current to be calculated by the following equation:

$$\text{Current per ring} = \frac{\text{watts output}}{\text{rotor voltage at stand-still} \times \sqrt{3} \times K}$$

This equation applies to three-phase rotors. For rotors wound for two phase, use 2 instead of the $\sqrt{3}$. K may be taken as 0.95 for motors of 150 kw. or larger. The factor K usually decreases as the size of motor is reduced, but no specific value can be stated for smaller sizes.

DETERMINATION OR APPROXIMATION OF LOSSES IN TRANSFORMERS

470 **No-Load Losses.** These shall be measured with open secondary circuit at the rated frequency, and with an applied primary voltage giving the rated secondary voltage plus the IR drop which occurs in the secondary under rated-load conditions. These no-load losses include core losses, consisting of hysteresis and eddy-current losses in the core, as well as dielectric loss in insulation due to electrostatic flux, which latter loss increases rapidly with temperature, and the test should therefore preferably be made at the reference temperature of 75°C.

471 **Stray Load-Losses.** These shall be measured by applying a primary voltage sufficient to produce rated-load current in the primary and secondary windings, the latter being short circuited. The stray load-losses will then be equal to the input decreased by the measured I^2R losses in both windings, as computed from resistance measurements at actual temperature, and the rated current. It is ordinarily immaterial whether the high-voltage or low-voltage winding is used as the primary winding in this test.

TESTS OF DIELECTRIC STRENGTH OF MACHINERY

480 **Basis for Determining Test Voltages.** The test voltage which shall be applied to determine the suitability of insulation for commercial operation is dependent upon the kind and size of the machinery, and its normal operating voltage, upon the nature of the service in which it is to be used, and upon the severity of the mechanical and electrical stresses to which it may be subjected. The voltages and other conditions of test which are recommended, have been determined as reasonable and proper for the great majority of cases, and are proposed for general adoption, except when specific reasons make a modification desirable.

481 **Condition of Machinery to be Tested.** Commercial tests shall, in general, be made with the completely assembled machinery and not with individual parts. The machinery shall be in good condition, and high-voltage tests, unless otherwise specified, shall be applied before the machine is put into commercial service, and shall

not be applied when the insulation resistance is low owing to dirt or moisture. High-voltage tests shall be made at the temperature assumed under normal operation or at the temperature attained under the conditions of commercial testing. High-voltage tests to determine whether specifications are fulfilled, are admissible on new machines only. Unless otherwise agreed upon, high-voltage tests of a machine shall be understood as being made at the factory.

482 **Points of Application of Voltage.** The test voltage shall be successively applied between each electric circuit and all other electric circuits and metal parts grounded.

483 **Interconnected Polyphase Windings** are considered as one circuit. All windings of a machine except that under test, shall be connected to ground.

484 **Frequency, Wave Form and Test Voltage.** The frequency of the testing circuit shall not be less than the rated frequency of the apparatus tested. A sine-wave form is recommended. See **§405.** The test shall be made with alternating voltage having a crest value equal to $\sqrt{2}$ times the specified test voltage. In d.c. machines, and in the general commercial application of a.c. machines, the testing frequency of 60 cycles per second is recommended.

485 **Duration of Application of Test Voltage.** The testing voltage for all classes of apparatus shall be applied continuously for a period of 60 seconds.

486 **Apparatus for Use on Single-Phase, 3-Phase-Delta or 3-Phase-Star Circuits.** Apparatus, such as transformers, which may be used in star connection on three-phase circuits, shall have the delta voltage of the circuits on which they may be used indicated on the rating plate and the test shall be based on such delta voltage.

VALUES OF A-C. TEST VOLTAGES

500 **The Standard Test for All Classes of Apparatus, Except as Otherwise Specified, Shall be Twice the Normal Voltage of the Circuit to Which the Apparatus is Connected, Plus 1000 Volts.**

501 *Exception*—**Alternating-Current Apparatus connected to Permanently Grounded Single-Phase Systems, for use on Permanently Grounded Circuits of more than 300 Volts,** shall be tested with 2.73 times the voltage of the circuit to ground + 1000 volts. **This** does not refer to three-phase apparatus with grounded star neutral.

502 *Exception*—**Distributing Transformers.** Transformers for primary pressures from 550 to 5000 volts, the secondaries of which are directly connected to consumers' circuits and commonly known as distributing transformers, shall be tested with 10,000 volts from primary to core and secondary combined. The secondary windings shall be tested with twice their normal voltage plus 1000 volts.

503 *Exception*—**Auto-Transformers** used for starting purposes, shall be tested with the same voltage as the test voltage of the apparatus to which they are connected.

504 *Exception*—**Household Devices.** Apparatus taking not over 660 watts† and intended solely for operation on supply circuits not exceeding 250 volts, shall be tested with 900 volts, except in the case of heating devices which shall be tested with 500 volts at operating temperature.

505 *Exception*—**Apparatus for use on Circuits of 25 Volts or Lower,** such as bell-ringing apparatus,* electrical apparatus used in automobiles, apparatus used on low-voltage battery circuits, etc., shall be tested with 500 volts.

506 *Exception*—**Field Windings of Alternating-Current Generators** shall be tested with 10 times the exciter voltage, but in no case with less than 1500 volts nor more than 3500 volts.

507 *Exception*—Field Windings‡ of Synchronous Machines, including motors and converters which are to be started from alternating-current circuits, shall be tested as follows:

a. When machines are started with fields short-circuited they shall be tested as specified in **§506**.

b. When machines are started with fields open-circuited and sectionalized while starting, they shall be tested with 5000 volts.

c. When machines are started with fields open-circuited and connected all series while starting, they shall be tested with 5000 volts for less than 250-volt excitation and 8000 volts for excitation of 250 volts to 750 volts.

508 *Exception.* **Phase-Wound Rotors of Induction Motors.** The secondary windings of wound rotors of induction motors shall be tested with twice their normal induced voltage, plus 1000 volts.

When induction motors with phase-wound rotors are reversed, while running at approximately normal speed, by reversing the primary connections, the test shall be four times the normal induced voltage, plus 1000 volts.

509 *Exception*—**Switches and Circuit Control Apparatus** above **600** volts, shall be tested with 2½ times rated voltage, plus 2000 volts. See **§720** to **741.**

510 *Exception*—**Assembled Apparatus.** Where a number of pieces of apparatus are assembled together and tested as an electrical unit, they shall be tested with 15 per cent lower voltage than the lowest required on any of the individual pieces of apparatus.

511 **Testing Transformers by Induced Voltage.** Under certain conditions it is permissible to test transformers by inducing the required voltage in their windings, in place of using a separate testing transformer. By "required voltage", is meant a voltage such that the line end of the windings shall receive a test to ground equal to that required by the general rules.

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†The present National Electric Code power limit for a single outlet.

*This rule does not include bell-ringing transformers of ratio 125 to 6 volts. See National Electric Code.

‡Series field coils should be regarded as part of the armature circuit and tested as such.

512 **Transformers with Graded Insulation** shall be so marked. They shall be tested by inducing the required test-voltage in the transformer and connecting the successive line leads to ground.

Transformer windings permanently grounded within the transformer shall be tested by inducing the required test voltage in such windings. (See **§500**).

MEASUREMENT OF VOLTAGE IN DIELECTRIC TESTS OF MACHINERY

530 **Use of Voltmeters and Spark-Gaps in Insulation Tests.** When making insulation tests on electrical machinery. every precaution must be taken against the occurrence of any spark-gap discharges in the circuits from which the machinery is being tested. A non-inductive resistance of about one ohm per volt shall be inserted in series with one terminal of the spark gap. If the test is made with one electrode grounded, this resistance shall be inserted directly in series with the non-grounded electrode. If neither terminal is grounded, one-half shall be inserted directly in series with each electrode. In any case this resistance shall be as near the measuring gap as possible and not in series with the tested apparatus. The resistance will damp high-frequency oscillations at the time of breakdown and limit the current which will flow. A water tube is the most reliable form of resistor. Carbon resistors should not be used because their resistance may become very low at high voltages.

531 For Machinery of Low Capacitance. When the machinery under test does not require sufficient charging current to distort the high-voltage wave shape, or change the ratio of transformation, the spark gap should be set for the required test voltage and the testing apparatus adjusted to give a voltage at which this spark gap just breaks down. This adjustment should be made with the apparatus under test disconnected. The apparatus should then be connected, and with the spark gap about 20 per cent longer, the testing apparatus is again adjusted to give the voltage of the former breakdown, which is the assumed voltage of test. This voltage is to be maintained for the required interval.

532 For Machinery of High Capacitance. When the charging current of the machinery under test may appreciably distort the voltage wave or change the effective ratio of the testing transformer, the first adjustment of voltage with the gap set for the test voltage should be made with the apparatus under test connected to the circuit and in parallel with the spark gap.

When making arc-over tests of large insulators, leads, etc. partial arc-over of the tested apparatus may produce oscillations which will cause the measuring gap to discharge prematurely. The measured voltage will then appear too high. In such tests the "equivalent" ratio" of the testing transformer should be measured by gap to within 20% of the arc-over voltage of the tested apparatus with the tested apparatus in circuit. The measuring gap should then be greatly

lengthened out and the voltage increased until the tested apparatus arcs over. This arc-over voltage should then be determined by multiplying the voltmeter reading by the equivalent ratio found above. Direct measurement of the spark-over voltage over one gap by another gap should always be avoided.

533 **Measurements with Voltmeter.** In measuring the voltage with a voltmeter, the instrument should preferably derive its voltage from the high-tension circuit, either directly, or by means of a voltmeter coil placed in the testing transformer, or through an auxiliary *ratio transformer*. It is permissible to measure the voltage at other places, such as the transformer primary provided corrections can be made for the variations in ratio caused by the charging current of the machinery under test, or provided there is no material variation of this ratio. In any case, when the capacitance of the apparatus to be tested is such as to cause wave distortion, the testing voltage must be checked by a spark gap as set forth in **§538**, or by a crest voltage meter. If the crest-voltage meter is calibrated in crest volts, its readings must be reduced to the corresponding r. m. s. sinusoidal value by dividing with $\sqrt{2}$.

534 **Measurements with Spark Gaps.** If proper precautions are observed, spark gaps may be used to advantage in checking the calibration of voltmeters when set up for the purposes of high-voltage tests of the insulation of machinery.

535 **Ranges of Voltages.** For the calibrating purposes set forth in **§534** the sphere-gap shall be used for voltages above 50 kv., and is to be preferred down to 30 kv. The needle spark-gap may, however, be used for voltages from 10 to 50 kv.

536 **The Needle Spark Gap.** The needle spark gap shall consist of new sewing needles, supported axially at the ends of linear conductors which are at least twice the length of the gap. There must be a clear space around the gap for a radius of at least twice the gap length.

537 The sparking distances in air between No. 00 sewing needle points for various root-mean-square sinusoidal voltages are as follows:

TABLE VII.

Needle-Gap Spark-Over Voltages

(At 25°C and 760 mm. barometer).

R M S Kilovolts	Millimeters	R.M.S. Kilovolts	Millimeters
10	11.9	35	51
15	18.4	40	62
20	25.4	45	75
25	33	50	90
30	41		

The above values refer to a relative humidity of 80 per cent. Variations from this humidity may involve appreciable variations in the sparking distance.

538 **The Sphere Spark-Gap.** The standard sphere spark-gap shall consist of two suitably mounted metal spheres. When used as specified below, the accuracy obtainable should be approximately 2 per cent.

No extraneous body, or external part of the circuit, shall be nearer the gap than twice the diameter of the spheres. By the "gap" is meant the shortest path between the two spheres.

The shanks should not be greater in diameter than 1/5th the sphere diameter. Metal collars, etc., through which the shanks extend, should be as small as practicable and should not, during any measurement, come closer to the sphere than the maximum gap length used in that measurement.

The sphere diameter should not vary more than 0.1 per cent and the curvature, measured by a spherometer, should not vary more than 1 per cent from that of a true sphere of the required diameter.

539 **In using the spherometer** to measure the curvature, the distance between the points of contact of the spherometer feet should be within the following limits:

TABLE VIII

Spherometer Specifications

Diameter of Sphere in m.m.	Distance between contact points in mm.	
	Maximum	Minimum
62.5	35	25
125	45	35
250	65	45
500	100	65

539A **In using Sphere Gaps** constructed as above, it is assumed that the apparatus will be set up for use in a space comparatively free from external dielectric fields. Care should be taken that conducting bodies forming part of the circuit, or at circuit potential, are not so located with reference to the gap that their dielectric fields are superposed on the gap; *e.g.*, the protecting resistance should not be arranged so as to present large masses or surfaces near the gap, even at a distance of two sphere diameters.

In case the sphere is grounded, the spark point of the grounded sphere should be approximately five diameters above the floor or ground.

540 The sparking distances between different spheres for various r.m.s sinusoidal voltages sha'l be assumed to be as follows:

TABLE IX.

Sphere-Gap Spark-Over Voltages

(At 25°C and 760 mm. barometric pressure)

Kilovolts	Sparking Distance in Millimeters.							
	62.5 mm. spheres		125 mm. spheres		250 mm. spheres		500 mm. spheres	
	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated
10	4.2	4.2	..	..	..	..	..	..
20	8.6	8.6	..	..	..	..	..	..
30	13.5	13.5	14.1	14.1	..	..	..	..
40	19.2	19.2	19.1	19.1	..	..	..	..
50	25.5	25.0	24.4	24.4	..	..	..	..
60	34.5	32.0	30.	30.	29	29	..	..
70	46.0	39.5	36	36	35	35	..	..
80	62.0	49.0	42	42	41	41	41	41
90		60.5	49	49	46	45	46	45
100			56	55	52	51	52	51
120			79.7	71	64	63	63	62
140			108	88	78	77	74	73
160			150	110	92	90	85	83
180				138	109	106	97	95
200					128	123	108	106
220					150	141	120	117
240					177	160	133	130
260					210	180	148	144
280					250	203	163	158
300						231	177	171
320						265	194	187
340							214	204
360							234	221
380							255	239
400							276	257

The sphere gap is more sensitive than the needle gap to momentary rises of voltage and the voltage required to spark over the gap should be obtained by slowly closing the gap under constant voltage, or by slowly raising the voltage with a fixed setting of the gap. Open arcs should not be permitted in proximity to the gap during its operation, as they may affect its calibration.

AIR-DENSITY CORRECTION-FACTORS FOR SPHERE GAPS

541 The Spark-Over Voltage, for a given gap, decreases with decreasing barometric pressure and increasing temperature. This correction may be considerable at high altitudes.

The spacing at which it is necessary to set a gap to spark over at some required voltage, is found as follows: Divide tne required voltage by the correction factor given below in Table X. A new voltage is thus obtained. The spacing on the standard curves obtained from Table IX, corresponding to this new voltage, is the required spacing.

The voltage at which a given gap sparks over is found by taking the voltage corresponding to the spacing from the standard curves of Table IX, and multiplying by the correction factor.

When the variation from sea level is not great, the relative air density may be used as the correction factor; when the variation is great, or greater accuracy is desired, the correction factor corresponding to the relative air density should be taken from Table X below, in which

$$\text{Relative air density} = \frac{0.392\, b}{273 + t}$$

b = barometric pressure in mm.

t = temperature in deg. C.

Corrected curves may be plotted for any given altitude, if desired.

Values of relative air density and corresponding values of the correction factor are tabulated below. It will be seen that for values above .9, the correction factor does not differ greatly from the relative air density.

TABLE X.

Air-Density Correction Factors for Sphere Gaps

Relative air density	Diameter of standard spheres in mm.			
	62.5	125	250	500
0.50	0.547	0.535	0.527	0.519
0.55	0.594	0.583	0.575	0.567
0.60	0.640	0.630	0.623	0.615
0.65	0.686	0.677	0.670	0.663
0.70	0.732	0.724	0.718	0.711
0.75	0.777	0.771	0.766	0.759
0.80	0.821	0.816	0.812	0.807
0.85	0.866	0.862	0.859	0.855
0.90	0.910	0.908	0.906	0.904
0.95	0.956	0.955	0.954	0.952
1.00	1.000	1.000	1.000	1.000
1.05	1.044	1.045	1.046	1.048
1.10	1.090	1.092	1.094	1.096

INSULATION RESISTANCE OF MACHINERY

550 **The insulation resistance of a machine** at its operating temperature shall be not less than that given by the following formula:

$$\text{Insulation Resistance in megohms} = \frac{\text{voltage at terminals}}{\text{rated capacity in kv-a.} + 1000}$$

The formula only applies to dry apparatus. Such high values are not attainable in oil-immersed apparatus.

Insulation resistance tests shall, if possible, be made at a d.c. pressure of 500 volts. Since the insulation resistance varies with the pressure, it is necessary that, if a pressure other than 500 volts is to be employed in any case, this other pressure shall be clearly specified.

The order of magnitude of the values obtained by this rule is shown in the following table:

TABLE XI.

Insulation Resistance of Machinery

Rated Voltage of machine	Megohms		
	100 kv-a.	1000 kv-a.	10,000 kv-a.
100	0.091	0.05	—
1,000	0.91	0.50	0.091
10,000	9.1	5.0	0.91
100,000	—	50	9.1

551 It should be noted that the insulation resistance of machinery is of doubtful significance by comparison with the dielectric strength. The insulation resistance is subject to wide variation with temperature, humidity and cleanliness of the parts. When the insulation resistance falls below that corresponding to the above rule, it can, in most cases of good design and where no defect exists, be brought up to the required standard by cleaning and drying out the machine. The insulation-resistance test may therefore afford a useful indication as to whether the machine is in suitable condition for the application of the dielectric test.

REGULATION

DEFINITIONS

560 **Regulation.** The regulation of a machine in regard to some characteristic quantity (such as terminal voltage or speed) is the change in that quantity occurring between any two loads. Unless otherwise specified, the two loads considered shall be zero load and rated load, and at the temperature attained under normal operation. The regulation may be expressed by stating the numerical values of the quantity at the two loads, or it may be ex-

pressed by the "percentage regulation", which is the percentage ratio of the change in the quantity occurring between the two loads, to the value of the quantity at either one or the other load, taken as the normal value. It is assumed that all parts of the machine affecting the regulation maintain constant temperature between the two loads, and where the influence of temperature is of consequence, a reference temperature of 75°C shall be considered as standard. If change of temperature should occur during the tests, the results shall be corrected to the reference temperature of 75°C.

The normal value may be either the no-load value, as the no-load speed of induction motors; or it may be the rated-load value, as in the voltage of a.c. generators.

It is usual to state the regulation of d-c. generators by giving the numerical values of the voltage at no load and rated load, and in some cases it is advisable to state regulation at intermediate loads.

561 The **Regulation of d-c. Generators** refers to changes in voltage corresponding to gradual changes in load and does not relate to the comparatively large momentary fluctuations in voltage that frequently accompany instantaneous changes in load.

In determining the regulation of a compound-wound d-c. generator, two tests shall be made, one bringing the load down and the other bringing the load up, between no-load and rated load. These may differ somewhat, owing to residual magnetism. The mean of the two results shall be used.

562 In **constant-potential a-c. generators,** the regulation is the rise in voltage (when the specified load at specified power factor is thrown off) expressed in per cent of normal rated-load voltage.

563 In **constant-current machines,** the regulation is the ratio of the maximum difference of current from the rated-load value (occurring in the range from rated-load to short-circuit, or minimum limit of operation), to the rated-load current.

564 In **constant-speed direct-current motors,** and induction motors, the regulation is the ratio of the difference between full-load and no-load speeds to the no-load speed.

565 In **constant-potential transformers,** the regulation is the difference between the no-load and rated-load values of the secondary terminal voltage at the specified power factor (with constant primary impressed terminal voltage) expressed in per cent of the rated-load secondary voltage, the primary voltage being adjusted to such a value that the apparatus delivers rated output at rated secondary voltage.

566 In **converters, dynamotors, motor-generators and frequency converters,** the regulation is the change in the terminal voltage of the output side between the two specified loads. This may be expressed by giving the numerical values, or as the percentage of the terminal voltage at rated load.

567 In **transmission lines, feeders etc.,** the regulation is the change in the voltage at the receiving end between rated non-inductive load and no load, with constant impressed voltage upon the sending

end. The percentage regulation is the percentage change in voltage to the normal rated voltage at the receiving end.

568 In **steam engines, steam turbines and internal combustion engines,** the percentage speed regulation is usually expressed as the percentage ratio of the maximum variation of speed, to the rated-load speed in passing slowly from rated load to no load (with constant conditions at the supply.)

569 If the test is made by passing suddenly from rated load to no load, the immediate percentage speed regulation so derived shall be termed the **fluctuation.**

570 In **a hydraulic turbine,** or other water motor, the percentage speed regulation is expressed as the percentage ratio of the maximum variation in speed in passing slowly from rated load to no load (at constant head of water), to the rated-load speed.

571 In **a generator unit,** consisting of a generator combined with a prime mover, the speed or voltage regulation should be determined at constant conditions of the prime mover; *i.e.* constant steam-pressure, head, etc. It includes the inherent speed variations of the prime mover. For this reason, the regulation of a generator unit is to be distinguished from the regulation of either the prime mover, or of the generator combined with it, when taken separately.

CONDITIONS FOR TESTS OF REGULATION

580 **Speed and Frequency.** The regulation of generators is to be determined at constant speed, and of alternating-current apparatus at constant frequency.

581 **Power Factor.** In apparatus generating, transforming or transmitting alternating currents, the power factor of the load to which the regulation refers should be specified. Unless otherwise specified, it shall be understood as referring to non-inductive load, that is to a load in which the current is in phase with the *e.m.f.* at the output side of the apparatus.

582 **Wave Form.** In the regulation of alternating-current machinery receiving electric power, a sine wave of voltage is assumed, except where expressly specified otherwise. See **§405.**

583 **Excitation.** In commutating machines, rectifying machines, and synchronous machines, such as direct-current generators and motors, as well as in alternating-current generators, the regulation is to be determined under such conditions as to maintain the field adjustment constant at that which gives rated-load voltage at rated-load current, as follows:

(1) In the case of separately-excited field magnets—constant excitation.

(2) In the case of shunt machines, constant resistance in the shunt-field circuit.

(3) In the case of series or compound machines, constant resistance shunting the series-field windings.

584 Tests and Computation of Regulation of A-C. Generators.

Any one of the three following methods may be used. They are given in the order of preference.

Method a.

The regulation can be measured directly, by loading the generator at the specified load and power factor, then reducing the load to zero, and measuring the terminal voltage, with speed and excitation adjusted to the same values as before the change. This method is not generally applicable for shop tests, particularly on large generators, and it becomes necessary to determine the regulation from such other tests as can be readily made.

585 Method b.

This consists in computing the regulation from experimental data of the open-circuit saturation curve and the zero-power-factor saturation curve. The latter curve, or one approximat-

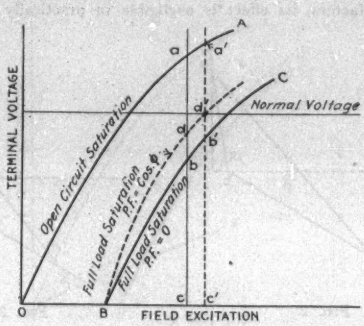


FIG. 1

ing very closely to it, can be obtained by running the generator with over excitation on a load of idle-running under-excited synchronous motors. The power factor under these conditions is very low and the load saturation curve approximates very closely the zero power factor saturation curve. From this curve and the open circuit curve, points for the load saturation curve, for any power factor, can be obtained by means of vector diagrams.

To apply Method b, it is necessary to obtain from test, the open-circuit saturation curve OA, Fig. 1, and the saturation curve BC at zero power factor and rated-load current. At any given excitation Oc, the voltage that would be induced on open circuit is ac, the terminal voltage at zero power factor is bc, and the apparent internal drop is ab. The terminal voltage dc at any other power factor can then be found by drawing an e.m.f. diagram* as in Fig. 2, where ϕ is

*Method b, for deducing the load saturation curve, at any assigned power factor, from no-load and zero-power-factor saturation curves obtained by test, must be regarded as empirical. Its value depends upon the fact that experience has demonstrated the reasonable correctness of the results obtained by it.

an angle such that $\cos \phi$ is the power factor of the load, $b\,e$ the resistance drop (IR) in the stator winding, ba the total internal drop, and ac the total induced voltage; ba and ac being laid off to correspond with the values obtained from Fig. 1. The terminal voltage at power factor $\cos \phi$, is then cb of Fig. 2, which, laid off in Fig. 1, gives point d. By finding a number of such points, the curve Bdd' for power factor $\cos \phi$ is obtained and the regulation at this power factor (expressed in per cent) is $\frac{100 \times a'd'}{d'\,c'}$, since $a'\,d'$ is the rise in voltage when the load at power factor $\cos \phi$ is thrown off at normal voltage $c'\,d'$.

Generally, the ohmic drop can be neglected, as it has very little influence on the regulation, except in very low-speed machines where the armature resistance is relatively high, or in some cases where regulation at unity power factor is being estimated. For low power factors, its effect is negligible in practically all cases. If

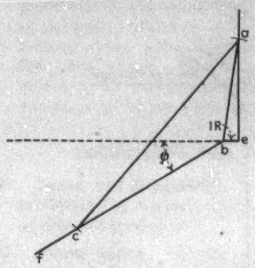


FIG. 2

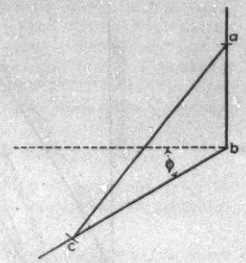


FIG. 3

resistance is neglected, the simpler e.m.f. diagram, Fig. 3, may be used to obtain points on the load saturation curve for the power factor under consideration.

586 **Method c.**

Where it is not possible to obtain by test a zero-power-factor saturation curve as in Method b, this curve can be estimated closely from open-circuit and short-circuit curves, by reference to tests at zero power factor on other machines of similar magnetic circuit. Having obtained the estimated zero-power-factor curve, the load saturation for any other power factor is obtained as in method b.

Thus Method c is the same as Method b; except that the zero-power-factor curve must be estimated. This may be done as follows. In Fig. 4, OA is the open-circuit saturation curve and OE the short-circuit line as shown by test. The zero-power-factor curve corresponding to any given current BF will start from point B, and for machines designed with low saturation and low reactance, will follow parallel to OA, as shown by the dotted curve BD, which is OA shifted horizontally parallel to itself by the distance OB. In high-speed machines, or in others

having low reactance and a low degree of saturation in the magnetic circuit, the zero-power-factor curve will lie quite close to BD, particularly in those parts that are used for determining the regulation. This is the case with many turbo-generators and high-speed water-wheel generators. In many cases, however, the zero-power-factor curve will deviate from BD, as shown by BC, and the deviation will be most pronounced in machines of high reactance, high saturation, and large magnetic leakage. The position of the actual curve BC with relation to BD, can be approximated with sufficient exactness by investigating the corresponding relation as obtained by test at zero power factor on machines of similar characteristics and magnetic circuit. Or curve BC can be calculated by methods based on the results of tests at zero power factor. After BC has been obtained, the saturation curve and regulation for any other power factor can be derived as in Method (b).

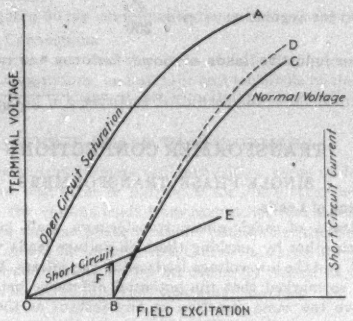


FIG. 4

587 Tests and Computation of Regulation for Constant-Potential Transformers.

The regulation can be determined by loading the transformer and measuring the change in voltage with change in load, at the specified power factor. This method is not generally applicable for shop tests, particularly on large transformers.

The regulation for any specified load and power factor can be computed from the measured impedance watts and impedance volts, as follows:

Let:

P = impedance watts, as measured in the short-circuit test at 75°C.

E_s = impedance volts, as measured in the short-circuit test.

IX = Reactance Drop in Volts.

I = Rated Primary Current.

E = Rated Primary Voltage.

q_r = percent drop in phase with current.
q_x = percent drop in quadrature with current.

$$IX = \sqrt{E_s^2 - \left(\frac{P}{I}\right)^2}$$

$$q_r = 100\frac{P}{EI}$$

$$q_x = 100\frac{IX}{E}$$

588 Then—

1. For **unity power factor**, we have approximately:-

$$\text{Per cent regulation} = q_r + \frac{q^2_x}{200}$$

589 2. For **inductive loads** of power-factor m and reactive-factor n,

$$\text{Per cent regulation} = mq_r + nq_x + \frac{(mq_x - nq_r)^2}{200}$$

TRANSFORMER CONNECTIONS

SINGLE-PHASE TRANSFORMERS

600 **Marking of Leads.**

The leads of single-phase transformers shall be distinguished from each other by marking the high-voltage leads with the letters A and B, and the low-voltage leads with the letters X and Y. They shall be so marked that the potential difference between A and B shall have the same direction at any instant as the potential difference between X and Y.

In accordance with the above rule, the terminals of single-phase transformers shall be marked as follows:

601 (1) High- and Low-Voltage Windings in Phase:

A ——— B
X ——— Y

602 (2) High- and Low-Voltage Windings 180 deg. Apart in Phase:

A ——— B
Y ——— X

603 **To operate transformers thus marked in parrallel,** it is only necessary to connect similarly marked terminals together, (provided that the reactances and resistances of the transformers are such as to permit of parallel operation).

604 **Single-Phase Transformers with More Than Two Windings.**

Transformers possessing three or more windings (each being provided with separate out-going leads), sha'l have the leads con-

nected to two of their windings, lettered in accordance with the preceding paragraph. The remaining leads shall be distinguished from the others by a subscript. For example, transformers possessing four secondary leads connected to two distinct similar windings for multiple-series operation, shall be lettered as follows:

$$\begin{array}{c} A \text{———} B \\ \left\{ \begin{array}{c} X \text{———} Y \\ X_1 \text{———} Y_1 \end{array} \right\} \end{array}$$

This indicates that the low-voltage winding consists of two disconnected parts, one part having terminals XY and the other part having terminals X_1Y_1. For multiple connection, X and X_1 are connected together and Y and Y_1 are connected together. For series connection, Y is connected to X_1.

605 Neutral Lead

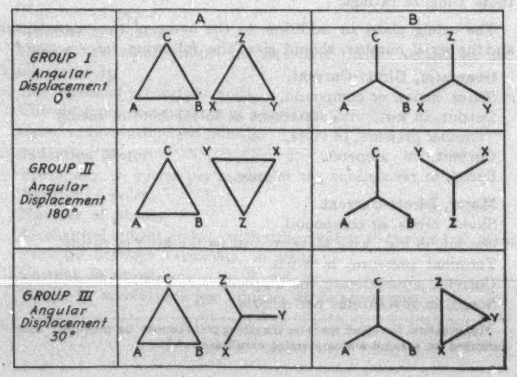
An out-going 50 per cent. (neutral) tap lead should be lettered N.

606 Internal Connections

The manufacturer shall furnish a complete diagrammatic sketch of internal connections, and all taps and terminals of the transformer shall be marked to correspond with numbers or letters in the sketch.

THREE-PHASE TRANSFORMERS

607 Three-phase transformers ordinarily have three or four leads for high-voltage, and three or four leads for low-voltage windings. To distinguish the various leads from each other, and also to distinguish between the various phase relations obtainable, the three high-voltage leads should be lettered A B C and the three low-voltage leads X Y Z. In addition, it should be distinctly stated in which of the three groups given in the following diagram the transformer belongs.



608 The rules given above for **single-phase transformers in regard to the neutral tap,** (See **§605**) and also in regard to internal connections, (See **§600** to **§604**) are applicable to three-phase transformers.

609 **Angular Displacement.**

The angular displacement between high- and low-voltage windings, is the angle in the diagram in **§607**, between the lines passing from the neutral point through A and X respectively. Thus, in Group 1, the angular displacement is zero degrees. In Group 2, the angular displacement is 180°, and in Group 3 the angular displacement is 30°.

610 **Parallel Operation of Three-Phase Transformers.**

Three-phase transformers, lettered in accordance with the above rules, will operate correctly in parallel, if at their rated loads, their percentage resistance drops are equal, and their percentage reactance drops, are equal. It is furthermore necessary that the angular displacements between high-voltage and low-voltage windings shall be equal, *i.e.* that the transformers shall belong to the same group in the diagram in **§607**. It is then only necessary to connect together similarly marked leads.

INFORMATION ON THE RATING PLATE OF A MACHINE

620 It is recommended that the rating plate of machines which comply with the Institute rules shall carry a distinctive special sign, such as "A.I.E.E. 1915 Rating" or "A15" Rating.

621 The absence of any statement to the contrary on the rating plate of a machine implies that it is intended for continuous service and for the standard altitude and ambient temperature of reference. See **§§287, 305, 308** and **309**.

622 The rating plate of a machine intended to work under various kinds of rating must carry the necessary information in regard to those kinds of ratings.

623 The rating plate, in addition to the name of the manufacturer and the serial number, should give the following information.*

624 **Generator, Direct-Current.**

Shunt, series, or compound.
Output, in kw., with statement as to the kind of rating.
Terminal pressure, in volts.
Current, in amperes.
Speed, in revolutions per minute.

625 **Motor, Direct-Current.**

Shunt, series, or compound.
Output, in kw., with statement as to the kind of rating.
Terminal pressure, in volts.
Current, approximate, in amperes.
Speed, in revolutions per minute.

*Information, for which space on the rating plate cannot be provided, shall be furnished on a supplementary rating certificate.

626 Transformer.

Frequency, in cycles per second.

Number of phases.

Output at the secondary terminals in kv-a., with statement as to the kind of rating.

High pressure, in volts.

Low pressure, in volts. See §§**202**, **203** and **204**.

Lead markings and diagram of internal connections, as set forth in §**600** to **609**.

627 Alternator.

Frequency, in cycles per second.

Number of poles.

Number of phases.

Output, in kv-a., with statement as to the kind of rating.

Power-factor corresponding to rated output.

Pressure between terminals, in volts, corresponding to the rated output.

Current in amperes.

Speed in revolutions per minute.

628 Synchronous Motor.

Frequency, in cycles per second.

Number of poles.

Number of phases.

Mechanical output, in kw., with statement as to the kind of rating.

Pressure between terminals, in volts, corresponding to the rated output.

Current in amperes.

If the motor is intended to work with a power factor different from unity, the necessary information shall be given.

Speed, in revolutions per minute.

629 Synchronous Converter.

Frequency in cycles per second.

Number of poles.

Number of phases.

Output at commutator in kilowatts, with statement as to kind of rating.

D-c. terminal pressure in volts.

Current from commutator in amperes.

Speed in revolutions per minute.

630 Induction Motor.

Frequency, in cycles per second.

Number of poles.

Number of phases.

Mechanical output, in kw., with statement as to the kind of rating.

Pressure between terminals, in volts.

Current, in amperes.

Speed, in revolutions per minute, at rated output.

STANDARDS FOR WIRES AND CABLES

TERMINOLOGY*

635 **Wire.**—A slender rod or filament of drawn metal.

The definition restricts the term to what would ordinarily be understood by the term "solid wire." In the definition, the word "slender" is used in the sense that the length is great in comparison with the diameter. If a wire is covered with insulation, it is properly called an insulated wire; while primarily the term "wire" refers to the metal, nevertheless when the context shows that the wire is insulated, the term "wire" will be understood to include the insulation.

636 **Conductor.**—A wire or combination of wires not insulated from one another, suitable for carrying a single electric current.

The term "conductor" is not to include a combination of conductors insulated from one another, which would be suitable for carrying several different electric currents.

Rolled conductors (such as busbars) are, of course, conductors, but are not considered under the terminology here given.

637 **Stranded Conductor.**—A conductor composed of a group of wires, or of any combination of groups of wires.

The wires in a stranded conductor are usually twisted or braided together.

638 **Cable.**—(1) A stranded conductor (single-conductor cable); or (2) a combination of conductors insulated from one another (multiple-conductor cable).

The component conductors of the second kind of cable may be either solid or stranded, and this kind of cable may or may not have a common insulating covering. The first kind of cable is a single conductor, while the second kind is a group of several conductors. The term "cable" is applied by some manufacturers to a solid wire heavily insulated and lead-covered; this usage arises from the manner of the insulation, but such a conductor is not included under this definition of "cable." The term "cable" is a general one, and, in practise, it is usually applied only to the larger sizes. A small cable is called a "stranded wire" or a "cord," both of which are defined below. Cables may be bare or insulated, and the latter may be armored with lead, or with steel wires or bands.

639 **Strand.**—One of the wires, or groups of wires, of any stranded conductor.

640 **Stranded Wire.**—A group of small wires, used as a single wire.

A wire has been defined as a slender rod or filament of drawn metal. If such a filament is subdivided into several smaller filaments or strands, and is used as a single wire, it is called a "stranded wire." There is no sharp dividing line of size between a "stranded wire" and a "cable." If used as a wire, for example in winding inductance coils or magnets, it is called a stranded wire and not a cable. If it is substantially insulated, it is called a "cord," defined below.

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*From Circular No. 37 of the Bureau of Standards.

641 **Cord.**—A small and very flexible cable, substantially insulated to withstand wear.

There is no sharp dividing line in respect to size between a "cord" and a "cable," and likewise no sharp dividing line in respect to the character of insulation between a "cord" and a "stranded wire." Rubber is used as the insulating material for many classes of cords.

642 **Concentric Strand.**—A strand composed of a central core surrounded by one or more layers of helically-laid wires or groups of wires.

643 **Concentric-Lay Cable.**—A single-conductor cable composed of a central core surrounded by one or more layers of helically-laid wires.

644 **Rope-Lay Cable.**—A single-conductor cable composed of a central core surrounded by one or more layers of helically-laid groups of wires.

This kind of cable differs from the preceding in that the main strands are themselves stranded.

645 **N-Conductor Cable.**—A combination of N conductors insulated from one another.

It is not intended that the name as here given be actually used. One would instead speak of a "3-conductor cable," a "12-conductor cable" etc. In referring to the general case, one may speak of a "multiple-conductor cable" (as in definition §638 above.)

646 **N-Conductor Concentric Cable.**—A cable composed of an insulated central conducting core with $(N-1)$ tubular stranded conductors laid over it concentrically and separated by layers of insulation.

This kind of cable usually has only two or three conductors. Such cables are used for carrying alternating currents. The remark on the expression "N-conductor" given for the preceding definition applies here also.

647 **Duplex Cable.**—Two insulated single-conductor cables, twisted together.

They may or may not have a common insulating covering.

648 **Twin Cable.**—Two insulated single-conductor cables laid parallel, having a common covering.

649 **Triplex Cable.**—Three insulated single-conductor cables twisted together.

They may or may not have a common insulating covering.

650 **Twisted Pair.**—Two small insulated conductors, twisted together, without a common covering.

The two conductors of a "twisted pair" are usually substantially insulated, so that the combination is a special case of a "cord."

651 **Twin Wire.**—Two small insulated conductors laid parallel, having a common covering.

SPECIFICATION OF SIZES OF CONDUCTORS

652 The sizes of solid wires shall be stated by their diameter in mils, the American Wire Gage (Brown and Sharpe) sizes being taken as standard. The sizes of stranded conductors shall be stated by their cross-sectional area in circular mils. For brevity, in cases where the most

careful specification is not required, the sizes of solid wires may be **stated by** the gage number in the American Wire Gage, and the sizes of **stranded** conductors smaller than 250,000 circular mils (*i.e.*, No. 0000 **A.W.G.** or smaller) may likewise be stated by means of the gage **number** in the American Wire Gage of a solid wire having the **same** cross-sectional area. Futhermore, an exception is made in the **case** of "Flexible Stranded Conductors," for which see **§655** below. In **stating large cross-sections,** it is sometimes convenient to use a circular inch (507 sq. mm.) instead of 1,000,000 circular mils.

STRANDING

653 Cables not requiring special flexibility shall be stranded in accordance with the following table.

TABLE XII

Standard Stranding of Concentric-Lay Cables

SIZE (See Note 1.)	Number of Wires. A Bare Cables for AERIAL USE*	B Weatherproof Cables for AERIAL USE*	C Insulated Cables
2.0 Cir. Inches	91	91	127
1.5	61	61	91
1.0	61	61	61
0.6	37	37	61
0.5	37	37	37
0.4	19	19	37
0000 A. W. G.	7	19	19
00	7	7	19
2	(See Note 2)	(See Note 2)	7
9	(See Note 2)	(See Note 2)	(See Note 2)

(1) For intermediate sizes, use stranding for next larger size.
(2) Solid Wire is recommended.

*Tentatively adopted pending ratification by other societies interested.

654 **Sectional Area of Cables.** The cross-sectional area of a cable shall be considered to be the sum of the cross-sectional areas of its component wires, when laid out straight and measured perpendicular to their axes.

655 **Flexible Stranding.** Conductors of special flexibility should ordinarily be made with wires of regular A.W.G. sizes, the number of wires and size being given. The approximate gage number or ap-

proximate circular mils of such flexible stranded conductors may be stated. The following stranding table is suggested.

TABLE XIII

Proposed Standard Stranding of Flexible Cables*

Nearest A. W. G. Size (See Note 1)	Circular Mils	Number of Wires	Size of Each Wire A. W. G.	Make-up (See Note 2)
–	1,102,941	427	16	61x7
–	874,496	427	17	"
–	693,448	427	18	"
–	549,976	427	19	"
–	436,394	427	20	"
–	345,913	427	21	"
–	274,390	427	22	"
–	264,698	259	20	37x7
0000	209,816	259	21	"
000	166,433	259	22	"
00	135,926	133	20	19x7
0	107,743	133	21	"
1	85,466	133	22	"
2	67,764	133	23	"
3	53,732	133	24	"
4	39,695	49	21	7x7
5	31,487	49	22	"
6	24,966	49	23	"
7	19,796	49	24	"
8	15,700	49	25	Optional (See Note 3)
9	12,451	49	26	"
10	9,854	49	27	"
11	7,830	49	28	"
12	6,208	49	29	"
Smaller		To equal required size	30	Bunched

Note 1. The A. W. G. sizes are approximated within 5 per cent.
Note 2. 61x7 signifies a rope-lay cable composed of 61 strands of 7 wires each.
Note 3. Rope-lay or bunched.

* This table is offered for consideration but will not be recommended for final adoption until ratified by other societies interested. The addition of another Table giving a further degree of flexibility is under consideration. The stranding of No. 4 A. W. G. and smaller sizes, is particularly open for discussion.

656 **Correction for Lay.** The resistance and mass of a stranded conductor are greater than in a solid conductor of the same cross-sectional area, depending on the lay (*i.e.*, the pitch of the twist of the wires). Two per cent shall be taken as the standard increment of resistance and of mass. In cases where the lay is definitely known, the increment should be calculated and not assumed.

The direction of lay is the lateral direction in which the strands of a cable run over the top of the cable as they recede from an observer looking along the axis of the cable.

CONDUCTIVITY OF COPPER.

675 The following I. E. C. rules are adopted:*

The following shall be taken as normal values for standard annealed copper:

(1) At a temperature of 20°C., the resistance of a wire of standard annealed copper one meter in length and of a uniform section of 1 square millimeter is 1/58 ohm = 0.017241 . . . . ohm.

(2) At a temperature of 20°C., the density of standard annealed copper is 8.89 grams per cubic centimeter.

(3) At a temperature of 20°C, the "constant mass" temperature coefficient of resistance of standard annealed copper, measured between two potential points rigidly fixed to the wire, is 0.00393 = 1/254.45 . . . . per degree centigrade.

(4) As a consequence, it follows from (1) and (2) that, at a temperature of 20 °C. the resistance of a wire of standard annealed copper of uniform section, one meter in length and weighing one gram, is (1/58) × 8.89 = 0.15328 . . . . . ohm.†§

676 **Copper Wire Tables.** The copper-wire Tables published by the Bureau of Standards in Circular No. 31 are adopted. These Tables are based upon the I. E. C. rules stated in **§675**.

HEATING AND TEMPERATURE OF CABLES.

677 **Maximum Safe Limiting Temperatures.**

The maximum safe limiting temperature in degrees C. at the surface of the conductor in a cable shall be:—

For impregnated paper insulation	(85—E)
" varnished cambric	(75—E)
" rubber insulation	(60—0.25E)

where E represents the r.m.s. operating e.m.f. in kilovolts between conductors.

Thus, at a working pressure of 3.3 kv., the maximum safe limiting temperature at the surface of the conductor, or conductors, in a cable would be:—

For impregnated paper	81.7°C.
" varnished cambric	71.7°C.
" rubber insulation	59.2°C.

ELECTRICAL TESTS.

678 **Lengths Tested.** Electrical tests of insulation on wires and cables shall be made on the entire lengths to be shipped.

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*See I. E. C. Publication No. 28 "International Standard of Resistance for Copper" March 1914.

†Paragraphs (1) and (4) of §675 define what are sometimes called "volume resistivity," and "mass resistivity" respectively. This may be expressed in other units as follows:— volume resistivity = 1.7241 microhm-cm. (or microhms in a cm. cube) at 20 °C. = 0.67879 microhm-inch at 20 °C., and mass resistivity = 875.20 ohms (mile, pound) at 20 °C.

§For detailed specifications of commercial copper, see the "Standard Specifications" of the American Society for Testing Materials.

679 **Immersion in Water.** Electrical tests of insulated conductors not enclosed in a lead sheath, shall be made while immersed in water after an immersion of twelve (12) hours, if insulated with rubber compound, or if insulated with varnished cambric. It is not necessary to immerse in water insulated conductors enclosed in a lead sheath.

In multiple-conductor cables, without waterproof overall jacket of insulation, no immersion test should be made on finished cables, but only on the individual conductors before assembling.

680 **Dielectric-Strength Tests. Object of Tests.** Dielectric tests are intended to detect weak spots in the insulation and to determine whether the dielectric strength of the insulation is sufficient for enabling it to withstand the voltage to which it is likely to be subjected in service, with a suitable factor of assurance.

The initially-applied voltage must not be greater than the working voltage, and the rate of increase shall not be over 100 per cent in 10 seconds.

681 **Factor of Assurance.** The factor of assurance of wire or cable insulation shall be the ratio of the voltage at which it is tested to that at which it is used.

682 **Test Voltage.** The dielectric strength of wire and cable insulation shall be tested at the factory, by applying an alternating test voltage between the conductor and sheath or water.

683 **The Magnitude and Duration of the Test Voltage** should depend upon the dielectric strength and thickness of the insulation, the length and diameter of the wire or cable, and the assurance factor required, the latter in turn depending upon the importance of the service in which the wire or cable is employed.

684 **The following test voltages** shall apply unless a departure is considered necessary, in view of the above circumstances. Rubber covered wires or cable for voltages up to 7 kv. shall be tested in accordance with the National Electric Code. Standardization for higher voltages for rubber insulated cables is not considered possible at the present time.

Varnished cambric and impregnated paper insulated wires or cables shall be tested at the place of manufacture for five (5) minutes in accordance with the Table XIV below.

TABLE XIV

Recommended Test Kilovolts Corresponding to Operating Kilovolts

Operating kv.	Test kv.	Operating kv.	Test kv.
Below 0.5	2.5*	5	14
0.5	3	10	25
1	4	15	3[illegible]
2	6.5	20	44
3	9	25	53
4	11.5		

*The minimum thickness of insulation shall be 1/16″ (1-6 mm.)

Different engineers specify different thickness of insulation for the same working voltages. Therefore, at the present time the test kv. corresponding to working kv. given in Table XIV are based on the **minimum** thickness of insulation specified by engineers and operating companies.†

685 **The Frequency of the Test Voltage** shall not exceed 100 cycles per second, and should approximate as closely as possible to a sine wave. The source of energy should be of ample capacity.

686 **Where Ultimate Break-Down Tests** are required, these shall be made on samples not more than 6 meters (20 ft.) long. The maximum allowable temperature at which the test is made for the particular type of insulation and the particular working pressure, shall not be greater than the temperature limits given in § 677.

687 **Multiple-Conductor Cables.** Each conductor of a multiple-conductor cable shall be tested against the other conductors connected together with the sheath or water.

INSULATION RESISTANCE

688 **Definition.** The insulation resistance of an insulated conductor is the electrical resistance offered by its insulation, to an impressed voltage tending to produce a leakage of current through the same.

689 **Insulation Resistance** shall be expressed in megohms for a specified length (as for a kilometer, or a mile, or one thousand feet), and shall be corrected to a temperature of 15.5° C. using a temperature coefficient determined experimentally for the insulation under consideration.

690 **Linear Insulation Resistance,** or the insulation resistance of Unit Length, shall be expressed in terms of the megohm-kilometer, or the megohm-mile, or the megohm-thousand-feet.

691 **Megohms Constant.** The Megohms Constant of an insulated conductor shall be the factor " K " in the equation

$$R = K \log_{10} \frac{D}{d}$$

where R = The insulation resistance, in megohms, for a specified unit length.

D = Outside diameter of insulation.

d = Diameter of conductor.

Unless otherwise stated, K will be assumed to correspond to the mile unit of length.

692 **Test.** The apparent insulation resistance should be measured after the dielectric-strength test, measuring the leakage current after a one-minute electrification, with a continuous e.m.f. of from 100 to 500 volts, the conductor being maintained positive to the sheath or water.

†The Standards Committee does not commit itself to the principle of basing test voltages on working voltages, but it is not yet in possession of sufficient data to base them upon the dimensions and physical properties of the insulation.

693 Multiple-Conductor Cables. The insulation resistance of each conductor of a multiple-conductor cable shall be the insulation resistance measured from such conductor to all the other conductors in multiple with the sheath or water.

CAPACITANCE OR ELECTROSTATIC CAPACITY

694 Capacitance is ordinarily expressed in microfarads. Linear Capacitance, or Capacitance per unit length, shall be expressed in Microfarads per unit length (kilometer, or mile, or one thousand feet) and shall be corrected to a temperature of 15.5° C.

695 Microfarads Constant. The Microfarads Constant of an insulated conductor shall be the factor "K" in the equation

$$C = \frac{K}{\text{Log}_{10}\dfrac{D}{d}}$$

where C = the capacitance in microfarads per unit length.

D = the outside diameter of insulation.

d = the diameter of conductor.

Unless otherwise stated, K will be assumed to refer to the mile unit of length.

696 Measurement of Capacitance. The Capacitance of low-voltage cable, shall be measured by comparison with a standard condenser. For long lengths of high-voltage cables, where it is necessary to know the true capacitance, the measurement should be made at a frequency approximating the frequency of operation.

697 Paired Cables. The capacitance shall be measured between the two conductors of any pair, the other wires being connected to the sheath or ground.

698 Electric Light and Power Cables. The capacitance of low-voltage cables is generally of but little importance. The capacitance of high-voltage cables should be measured between the conductors, and also between each conductor and the other conductors connected to the lead sheath or ground.

699 Multiple-Conductor Cables (not paired). The capacitance of each conductor of a multiple-conductor cable shall be the capacitance measured from such conductor to all of the other conductors in multiple with the sheath or the ground.

STANDARDS FOR SWITCHES AND OTHER CIRCUIT-CONTROL APPARATUS*

SWITCHES

720 **The following Rules apply to Switches** of above 600 volts. (For 600 volts and below, see National Electric Code.†)

721 **Definition.** A switch is a device for making, breaking, or changing connections in an electric circuit.

722 **Rating.**

(a) By amperes to be carried with not more than 30 °C. rise on contacts and current-carrying parts.

(b) By normal voltage of circuit on which it may be used.

723 **Performance and Tests.**

(a) **Heating Test** with rated current applied continuously until temperature is constant; ambient temperature 40 °C.

(b) **Dielectric Test** at 2½ times rated voltage plus 2000. See §509.

CIRCUIT BREAKERS

724 **Definition.** A device designed to open a current-carrying circuit without injury to itself. A circuit breaker‡ may be:

(a) An automatic circuit-breaker, which is designed to trip automatically under any predetermined condition of the circuit, such as an underload or overload of current or voltage.

(b) A manually tripped circuit-breaker, which is designed to be tripped by hand.

Both types of operation may be combined in one and the same device.

725 **Rating.**

(a) By normal current-carrying capacity.

(b) By normal voltage.

(c) By amperes which it can interrupt at normal voltage of the circuit.

726 **Performance and Tests.** The heating test shall be made with normal current. In oil circuit breakers the same oil must be used for heating tests as for rupturing tests. The rise of temperature at the contacts shall not exceed 30 °C. The Rise on tripping solenoids and accessory parts not to exceed 50 °C. Ambient temperature of reference, 40 °C.

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*These rules do not apply to magnetically-operated or air-operated switches used for motor control.

†By the term "Code" is meant "National Electrical Code" as recommended by the National Fire Protection Association.

‡These rules refer only to circuit breakers of above 550 volts. For 550 volts and below, see the National Electric Code.

727 **Dielectric Test.** Same as **§723.**

728 **Rupturing Test** must be made with the current specified under **§725** (c), and at normal voltage.

NOTE. Although circuit breakers should be considered as devices alone, no account being taken, in the rating, of the system on which they are to be used: yet in applying circuit breakers to any given service, it may be necessary to take into account the system on which they are to be used, with all its characteristics.

Allowances must be made for the reactance, resistance, etc., of the circuit to be controlled, as these have a direct bearing on the maximum current flow.

In some systems it has been found that the pressure rises so high during switching, that higher insulation tests than that specified in **§723** should be given.

FUSES

(For circuits up to and including 600 volts, see National Electric Code)

729 **Definition.** A fuse is an element designed to melt or dissipate at a predetermined current value, and intended to protect against abnormal conditions of current.

NOTE. (The terminals, tubes, etc. which go with the fuse proper are included in the definition).

730 **Rating.** Fuses shall be rated at the maximum current which they are required to carry continuously, and at the normal voltage of the circuit on which they are designed to be used.

Fuses may be divided into two classes:

(1) Those designed to protect the circuit and apparatus both against short circuit and against definite amounts of overload (*e.g.* fuses of the National Electric Code which open on 25 per cent overload).

(2) Those designed to protect the system only against short circuits; (*e.g.* expulsion fuses, which blow at several times the current which they are designed to carry continuously). The line separating these two classes is not definitely fixed.

731 **Temperature.** Coils or windings (such as accompany fuses of the magnetic blow-out type) should not exceed the limits set for machine coils having the same character of insulation. (See **§§376** to **379**). The highest temperature for the fuse proper should not exceed the safe limit for the material employed (*e.g.* the temperature of the fibre tube of an enclosed fuse should not exceed the safe limit for this material, but an open-link metal fuse may be run at any temperature which will not injure the fuse material; except that no application of the above rule shall contravene the National Electric Code).

732 **Test.** For fuses intended for use on circuits of small capacity, or in protected positions on systems of large capacity, see Nation-

NOTE. Complete standardization of these fuses above 600 volts, according to the method of the National Electric Code, is not advisable at this time, but is expected to be accomplished by an eventual extension of the National Electric Code. Until such extension is made, the following definitions and ratings may be followed.

al Electric Code. For large power fuses intended for service similar to that required of circuit breakers, see **§724** to **728**, or the National Electric Code, as far as the latter applies.

LIGHTNING ARRESTERS

733 Definition. A lightning arrester is a device for protecting circuits and apparatus against lightning or other abnormal potential rises of short duration.

734 Rating. Arresters shall be rated by the voltage of the circuit on which they are to be used.

Lightning arresters may be divided into two classes:

(a) Those intended to discharge for a very short time.

(b) Those intended to discharge for a period of several minutes.

735 Performance and Tests. Dielectric Test same as **§723.**

The resistance of the arrester at double potential and also at normal potential, shall be determined by observing the discharge currents through the arrester.

(c) In the case of any arrester using a gap, a test shall be made of the spark potential on either direct-current or 60-cycle a-c. excitation.

(d) The equivalent sphere gap under disruptive discharge shall also be measured, using a considerable quantity of electricity.

(e) The endurance of the arrester to continuous surges shall be tested.

PROTECTIVE REACTORS

736 Definition. A reactor (See **§82** and **214**) is a device for protecting circuits by limiting the current flow and localizing the disturbance under short-circuit conditions.

737 Rating.

(a) In kilovolt-amperes absorbed by normal current.

(b) By the normal current, frequency and line (delta) voltage for which the reactor is designed.

(c) By the current which the device is required to stand under short-circuit conditions.

738 Performance and Tests.

The Heat Test shall be made with normal current and frequency applied until the temperature is constant. The temperature should not exceed the safe limits for the materials employed. See **§§376** to **379.**

739 Dielectric Test. $2\frac{1}{2}$ times line voltage plus 2000, for one minute, from conductor to ground.

NOTE. The reactor shall be so designed as to be capable of withstanding, without mechanical injury, rated current at normal frequency, suddenly applied.

RESISTOR OR RHEOSTAT

740 Definition. Any device heretofore commonly known as a resistance, used for operation or control. **(§81)** See National Electric Code.

INSTRUMENT TRANSFORMERS

741 **Definition.** An instrument transformer is a transformer for use with measuring instruments, in which the conditions in the primary circuit as to current and voltage are represented with high numerical accuracy in the secondary circuit.

Under this heading and for more general use:

(a) A current transformer is a transformer designed for series connection in its primary circuit with the ratio of transformation appearing as a ratio of currents.

(b) A potential (voltage) transformer is a transformer designed for shunt or parallel connection in its primary circuit, with the ratio of transformation appearing as a ratio of potential differences (voltages).

For further definitions relative to instrument transformers, see 205-207.

For the dielectric test of potential transformers, see §500, and for the dielectric test of current transformers, see §509.

Further standards concerning instrument transformers are still under discussion.

STANDARDS FOR ELECTRIC RAILWAYS

DEFINITIONS

760 **Transmission System:** When the current generated for an electric railway is changed in kind or voltage, between the generator and the cars or locomotives, that portion of the conductor system carrying current of a kind or voltage substantially different from that received by the cars or locomotives, constitutes the *transmission system.**

761 **Distribution System:** That portion of the conductor system of an electric railway which carries current of the kind and voltage received by the cars or locomotives, constitutes the *distribution system.**

762 **Substation:** A substation is a group of apparatus or machinery which receives current from a transmission system, changes its kind or voltage, and delivers it to a distribution system.

RATING OF RAILWAY SUBSTATION MACHINERY

763 **Continuous Rating.** The rating of a substation machine shall be the kv-a. output at a stated power factor input, which it will deliver continuously with temperatures or temperature rises not exceeding the limiting values given in Sections **376** and **379** and also fulfilling the other requirements set forth in these rules and summarized in Section **260**.

764 **Momentary Loads.** These machines should be capable of carrying a load of twice their rating for one minute, after a continuous run at rated load, without disqualifying them for continuous service.

765 **Nominal Rating.** Where the continuous rating is inconvenient, the following nominal rating may be used. The nominal rating of a substation machine shall be the kv-a. output at a stated power factor input, which, having produced a constant temperature in the machine may be increased 50 per cent for two hours, without producing temperatures or temperature rises exceeding by more than 5°C. the limiting values given in §**376** and **379**. These machines should be capable of carrying a load of twice their nominal rating for a period of one minute, without disqualifying them for continuous service. The name plate should be marked "nominal rating."

CONDUCTOR AND RAIL SYSTEMS.

766 **Contact Conductors.** That part of the distribution system other than the traffic rails, which is in immediate electrical contact with

*These definitions are identical in sense, although not in words, with those of the Interstate Commerce Commission, as given in their Classification of Accounts for Electric Railways.

the circuits of the cars or locomotives, constitutes the contact conductors.

767 **Contact Rail:** A rigid contact conductor.

768 OVERHEAD CONTACT RAIL: A contact rail above the elevation of the maximum equipment line.†

769 THIRD RAIL: A contact conductor placed at either side of the track, the contact surface of which is a few inches above the level of the top of the track rails.

770 CENTER CONTACT RAIL: A contact conductor placed between the track rails, having its contact surface above the ground level.

771 UNDERGROUND CONTACT RAIL: A contact conductor placed beneath the ground level.

772 GAGE OF THIRD RAIL: The distance, measured parallel to the plane of running rails, between the gage line of the nearer track rail and the inside gage line of the *contact surface* of the third rail.

773 ELEVATION OF THIRD RAIL: The elevation of the contact-surface of the third rail, with respect to the plane of the tops of running rails.

774 STANDARD GAGE OF THIRD RAILS: The gage of third rails shall be not less than 26 inches (66 cm.) and not more than 27 inches (68.6 cm.).

775 STANDARD ELEVATION OF THIRD RAILS: The elevation of third rails shall be not less than 2¾ inches (70 mm.), and not more than 3½ inches (89 mm.).

776 THIRD RAIL PROTECTION: A guard for the purpose of preventing accidental contact with the third rail.

777 **Trolley Wire:** A flexible contact conductor, customarily supported above the cars.

778 **Messenger Wire or Cable:** A wire or cable running along with and supporting other wires, cables or contact conductors.

A primary messenger is directly attached to the supporting system. A secondary messenger is intermediate between a primary messenger and the wires, cables or contact conductors.

779 **Classes of Construction:** Overhead trolley construction will be classed as *Direct Suspension* and *Messenger or Catenary Suspension.*

780 DIRECT SUSPENSION: All forms of overhead trolley construction in which the trolley wires are attached, by insulating devices, directly to the main supporting system.

781 MESSENGER OR CATENARY SUSPENSION: All forms of overhead trolley construction in which the trolley wires are attached, by suitable devices, to one or more messenger cables, which in turn may be carried either in *Simple Catenary, i.e.*, by primary messengers, or in *Compound Catenary, i.e.*, by secondary messengers.

782 SUPPORTING SYSTEMS shall be classed as follows:

783 SIMPLE CROSS-SPAN SYSTEMS: Those systems having at each support a single flexible span across the track or tracks.

†The contour which embraces cross-sections of all rolling stock under all normal operating conditions.

784 MESSENGER CROSS-SPAN SYSTEMS: Those systems having at each support two or more flexible spans across the track or tracks, the upper span carrying part or all of the vertical load of the lower span.

785 BRACKET SYSTEMS: Those systems having at each support an arm or similar rigid member, supported at only one side of the track or tracks.

786 BRIDGE SYSTEMS: Those systems having at each support a rigid member, supported at both sides of the track or tracks.

787 STANDARD HEIGHT OF TROLLEY WIRE ON STREET AND INTERURBAN RAILWAYS: It is recommended that supporting structures shall be of such height that the lowest point of the trolley wire shall be at a height of 18 feet (5.5m.) above the top of rail under conditions of maximum sag, unless local conditions prevent. On trackage operating electric and steam road equipment and at crossings over steam roads, it is recommended that the trolley wire shall be not less than 21 feet (6.4m.) above the top of rail, under conditions of maximum sag.

RAILWAY MOTORS

RATING

800 **Nominal Rating**: The nominal rating of a railway motor shall be the mechanical output at the car or locomotive axle, measured in kilowatts, which causes a rise of temperature above the surrounding air, by thermometer, not exceeding 90 °C. at the commutator, and 75 °C. at any other normally accessible part after one hour's continuous run at its rated voltage (and frequency in the case of an alternating-current motor) on a stand with the motor covers arranged to secure maximum ventilation without external blower. The rise in temperature as measured by resistance, shall not exceed 100 °C.*

801 The statement of the nominal rating shall also include the corresponding voltage and armature speed.

802 **Continuous Rating:** The continuous ratings of a railway motor shall be the *inputs* in amperes at which it may be operated continuously at $\frac{1}{2}$, $\frac{3}{4}$ and full voltage respectively, without exceeding the specified temperature rises (see **§805**), when operated on stand test with motor covers and cooling system, if any, arranged as in service. Inasmuch as the same motor may be operated under different conditions as regards ventilation, it will be necessary in each case to

*This definition differs from that in the 1911 edition of the Rules, principally by the substitution of a kilowatt rating for the horse-power rating and the omission of a reference to a room temperature of 25 °C. The horse-power rating of a railway motor may, for practical purposes, be taken as $\frac{3}{4}$ of the kilowatt rating. On account of the hitherto prevailing practise of expressing mechanical output in horse-power, it is recommended that, for the present, the capacity be expressed both in kilowatts and in horse-power, a double rating, namely,

kw.——————approx. equiv. h.p.——————

In order to lay stress upon the preferred future basis, it is desirable that on rating plates, the rating in kilowatts shall be shown in larger and more prominent characters than the capacity in horse power.

define the system of ventilation which is used. In case motors are cooled by external blowers, the flow of air on which the rating is based shall be given.

803 **Maximum Input.** The subject of momentary loads for railway motors is under investigation.

TEMPERATURE LIMITATIONS

804 **The allowable temperature** in any part of a motor in service will be governed by the kind of material with which that part is insulated. In view of space limitations, and the cost of carrying dead weight on cars, it is considered good practice to operate railway motors for short periods at higher temperatures than would be advisable in stationary motors. The following temperatures are permissible:

TABLE XV
Operating Temperatures of Railway Motors

Class of Material See §376 to 379.	Maximum Observable Temperature of windings when in continuous service.	
	By Thermometer See §345	By Resistance
A	85	110
B	100	130

For infrequent occasions, due to extreme ambient temperatures, it is permissible to operate at 15° higher temperature.

805 With a view to not exceeding the above temperature limitations, the continuous ratings shall be based upon the **temperature rises** tabulated below:

TABLE XVI
Stand-Test Temperature Rises of Railway Motors*

Class of Material See §376 to 379	Temperature Rises of windings	
	By Thermometer See §345	By Resistance
A	65	85
B	80	105

*The temperature rise in service may be very different from that on stand test. See §1104 for relation between stand test and service temperatures, as affected by ventilation.

806 **Field-Control Motors.** The nominal and continuous ratings of field-control motors shall relate to their performance with the operating field which gives the maximum motor rating. Each section of the field windings shall be adequate to perform the service required of it, without exceeding the specified temperature rises.

CHARACTERISTIC CURVES

810 **The Characteristic Curves** of railway motors shall be plotted with the current as abscissas and the tractive effort, speed and efficiency as ordinates. In the case of a-c. motors, the power factor shall also be plotted as ordinates.

811 **Characteristic curves of direct-current motors** shall be based upon full voltage, which shall be taken as 600 volts, or a multiple thereof.

812 **In the case of field-control motors,** characteristic curves shall be given for all operating field connections.

EFFICIENCY AND LOSSES

815 **The efficiency** of railway motors shall be deduced from a determination of the losses enumerated in **§816** to **820.** (See also **§ 1100** and **1101.**)

816 **The copper loss** shall be determined from resistance measurements corrected to 75° C.

817 **The no-load core loss, brush friction, armature-bearing friction and windage** shall be determined as a total under the following conditions:

In making the test, the motor shall be run without gears. The kind of brushes and the brush pressure shall be the same as in commercial service. With the field separately excited, such a voltage shall be applied to the armature terminals as will give the same speed for any given field current as is obtained with that field current when operating at normal voltage under load. The sum of the losses above-mentioned, is equal to the product of the counter-electromotive force and the armature current.

818 The **core loss** in d-c. motors shall be separated from the friction and windage losses above described by measuring the power required to drive the motor at any given speed without gears, by running it as a series motor on low voltage and deducting this loss from the sum of the no-load losses at corresponding speed. (See **§1101** for alternative method).

The friction and windage losses under load shall be assumed to be the same as without load, at the same speed.

The core loss under load shall be assumed as follows:

TABLE XVII

Core Loss in D. C. Railway Motors at Various Loads.

Per cent of Input at Nominal Rating	Loss as Per cent of No-load Core Loss
200	165
150	145
100	130
75	125
50	123
25 and under	122

Note:—With motors designed for field control the core losses shall be assumed as the same for both full and permanent field. It shall be the mean between the no-load losses at full and permanent field, increased by the percentages given in the above Table.

819 **The brush-contact resistance loss** to be used in determining the efficiency, may be obtained by assuming that the sum of the drops at the contact surfaces of the positive and negative brushes is three volts.

820 The losses in gearing and axle bearings for single-reduction single-geared motors, varies with type, mechanical finish, age and lubrication. The following values, based on accumulated tests, shall be used in the comparison of single-reduction single-geared motors.

TABLE XVIII

Losses in Axle Bearings and Single-Reduction Gearing of Railway Motors.

Per Cent of Input at Nominal Rating	Losses as Per Cent of Input
200	3.5
150	3.0
125	2.7
100	2.5
75	2.5
60	2.7
50	3.2
40	4.4
30	6.7
25	8.5

Note:—Further investigation may indicate the desirability of giving separate values of the losses for full and tapped fields, or low- and high-speed motors.

ELECTRIC LOCOMOTIVES

830 **Rating.** Locomotives shall be rated in terms of the weight on drivers, nominal one-hour tractive effort, continuous tractive effort and corresponding speeds.

831 **Weight on Drivers.** The weight on drivers, expressed in pounds, shall be the sum of the weights carried by the drivers and of the drivers themselves.

832 **Nominal Tractive Effort:** The nominal tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers, when the motors are operating at their nominal (one-hour) rating.

833 **Continuous Tractive Effort.** The continuous tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers when the motors are operating at their full-voltage continuous rating, as indicated in **§802**.

In the case of locomotives operating on intermittent service, the continuous tractive effort may be given for $\frac{1}{2}$ or $\frac{3}{4}$ voltage, but in such cases the voltage shall be clearly specified.

834 **Speed:** The rated speed, expressed in miles per hour, shall be that at which the continuous tractive effort is exerted.

See also Appendix II on Additional Standards for Railway Motors.

ILLUMINATION AND PHOTOMETRY

The following Sections, **850** to **895**, are the rules of the Nomenclature and Standards Committee of the Illuminating Engineering Society. They are here included by permission.

850 **Luminous flux** is radiant power evaluated according to its capacity to produce the sensation of light.

851 **The stimulus coefficient** K_λ for radiation of a particular wave-length, is the ratio of the luminous flux to the radiant power producing it.

852 **The mean value of the stimulus coefficient,** K_m, over any range of wave-lengths, or for the whole visible spectrum of any source, is the ratio of the total luminous flux (in lumens) to the total radiant power (in ergs per second, but more commonly in watts).

853 **The luminous intensity** of a point source of light is the solid angular density of the luminous flux emitted by the source in the direction considered; or it is the flux per unit solid angle from that source.

Defining equation:

Let I be the intensity, F the flux and ω the solid angle.

Then
$$I = \frac{dF}{d\omega}$$

or, if the intensity is uniform,

$$I = \frac{F}{\omega},$$

854 **Illumination**, on a surface, is the luminous flux-density over that surface, or the flux per unit of intercepting area.

Defining equation:

Let E be the illumination and S the area of the intercepting surface.

Then
$$E = \frac{dF}{dS},$$

or, when uniform,

$$E = \frac{F}{S},$$

855 **Candle**, the unit of luminous intensity maintained by the National Laboratories of France, Great Britain, and the United States.[1]

856 **Candle-power**, luminous intensity expressed in candles.

1 This unit, which is used also by many other countries, is frequently referred to as the international candle.

857 **Lumen,** the unit of luminous flux, equal to the flux emitted in a unit solid angle (steradian) by a point source of one candle-power.[2]

858 **Lux,** a unit of illumination equal to one lumen per square meter. The C. G. S. unit of illumination is one lumen per square centimeter. For this unit Blondel has proposed the name "Phot." One millilumen per square centimeter (milliphot) is a practical derivative of the C. G. S. system. One foot-candle is one lumen per square foot and is equal to 1.0764 milliphots.

859 **Exposure,** the product of an illumination by the time. Blondel has proposed the name "phot-second" for the unit of exposure in the C. G. S. system.

860 **Specific luminous radiation,** the luminous flux-density emitted by a surface, or the flux emitted per unit of emissive area. It is expressed in lumens per square centimeter.

Defining equation:

Let E' be the specific luminous radiation.

Then, for surfaces obeying Lambert's cosine law of emission.

$$E' = \pi b_0.$$

861 **Brightness,** b, of an element of a luminous surface from a given position, may be expressed in terms of the luminous intensity per unit area of the surface projected on a plane perpendicular to the line of sight, and including only a surface of dimensions negligibly small in comparison with the distance to the observer. It is measured in candles per square centimeter of the projected area.

Defining equation:

Let θ be the angle between the normal to the surface and the line of sight.

Then
$$b = \frac{dI}{dS \cos\theta}$$

862 **Normal brightness,** b_0, of an element of a surface (sometimes called specific luminous intensity) is the brightness taken in a direction normal to the surface.[3]

Defining equation:

$$b_0 = \frac{dI}{dS},$$

or, when uniform,
$$b_0 = \frac{I}{S}$$

Brightness may also be expressed in terms of the specific luminous radiation of an ideal surface of perfect diffusing qualities, *i. e.*, one obeying Lambert's cosine law.

2 A uniform source of one candle emits 4π lumens.

3 In practice, the brightness b of a luminous surface or element thereof is observed, and not the normal brightness b_0. For surfaces for which the cosine law of emission holds, the quantities b and b_0 are equal.

863 **The Lambert, the C. G. S. Unit of Brightness,** the brightness of a perfectly diffusing surface radiating or reflecting one lumen per square centimeter. This is equivalent to the brightness of a perfectly diffusing surface having a coefficient of reflection equal to unity and illuminated by one phot.

864 **For most purposes, the millilambert** (0.001 lambert) is the preferable practical unit. A perfectly diffusing surface emitting one lumen per square foot will have a brightness of 1.076 millilamberts.

865 **Brightness expressed in candles per square centimeter** may be reduced to Lamberts by multiplying by π.

Brightness expressed in candles per square inch may be reduced to foot-candle brightness, by multiplying by the factor $144\,\pi = 452$.

Brightness expressed in candles per square inch may be reduced to lamberts by multiplying by $\pi/6.45 = 0.4868$.

In practice, no surface obeys exactly Lambert's cosine law of emission; hence the brightness of a surface in lamberts is, in general not numerically equal to its specific luminous radiation in lumens per square centimeter.

Defining equations:

$$L = \frac{dF}{dS}$$

Or when uniform

$$L = \frac{F}{S}$$

866 **Coefficient of reflection,** the ratio of the total luminous flux reflected by a surface to the total luminous flux incident upon it. It is a simple numeric. The reflection from a surface may be regular, diffuse or mixed. In perfect regular reflection, all of the flux is reflected from the surface at an angle of reflection equal to the angle of incidence. In perfect diffuse reflection, the flux is reflected from the surface in all directions, in accordance with Lambert's cosine law. In most practical cases, there is a superposition of regular and diffuse reflection.

867 **Coefficient of regular reflection** is the ratio of the luminous flux reflected regularly to the total incident flux.

868 **Coefficient of diffuse reflection** is the ratio of the luminous flux reflected diffusely to the total incident flux.

Defining equation:

Let m be the coefficient of reflection (regular or diffuse).

Then, for any given portion of the surface,

$$m = \frac{E'}{E}$$

869 **Lamp,** a generic term for an artificial source of light.

870 **Primary luminous standard,** a recognized standard luminous source reproducible from specifications.

871 **Representative luminous standard,** a standard of luminous intensity adopted as the authoritative custodian of the accepted value of the unit.

872 **Reference standard,** a standard calibrated in terms of the unit from either a primary or representative standard and used for the calibration of working standards.

873 **Working standard,** any standardized luminous source for daily use in photometry.

874 **Comparison lamp,** a lamp of constant but not necessarily known candle-power, against which a working standard and test lamps are successively compared in a photometer.

875 **Test lamp,** in a photometer,—a lamp to be tested.

876 **Performance curve,** a curve representing the behavior of a lamp in any particular (candle-power, consumption, etc.) at different periods during its life.

877 **Characteristic curve,** a curve expressing a relation between two variable properties of a luminous source, as candle-power and volts, candle-power and rate of fuel consumption, etc.

878 **Horizontal Distribution Curve.** A polar curve representing the luminous intensity of a lamp, or lighting unit, in a plane perpendicular to the axis of the unit, and with the unit at the origin.

879 **Vertical Distribution Curve.** A polar curve representing the luminous intensity of a lamp, or lighting unit, in a plane passing through the axis of the unit, and with the unit at the origin. Unless otherwise specified, a vertical distribution curve is assumed to be an *average* vertical distribution curve, such as may in many cases be obtained by rotating the unit about its axis and measuring the average intensities at the different elevations. It is recommended that in vertical distribution curves, angles of elevation shall be counted positively from the nadir as zero, to the zenith as 180 degrees. In the case of incandescent lamps, it is assumed that the vertical distribution curve is taken with the tip downward.

880 **Mean horizontal candle-power** of a lamp,—the average candle-power in the horizontal plane passing through the luminous center of the lamp.

It is here assumed that the lamp (or other light source) is mounted in the usual manner, or, as in the case of an incandescent lamp, with its axis of symmetry vertical.

881 **Mean spherical candle-power** of a lamp,—the average candle-power of a lamp in all directions in space. It is equal to the total luminous flux of the lamp, in lumens, divided by 4π.

882 **Mean hemispherical candle-power** of a lamp (upper or lower),—the average candle-power of a lamp in the hemisphere considered. It is equal to the total luminous flux emitted by the lamp, in that hemisphere, divided by 2π.

883 **Mean zonal candle-power** of a lamp,—the average candle-power of a lamp over the given zone. It is equal to the total luminous flux emitted by the lamp in that zone, divided by the solid angle of the zone.

884 **Spherical reduction factor** of a lamp,—the ratio of the mean spherical to the mean horizontal candle-power of the lamp.[4]

885 **Photometric Tests** in which the results are stated in candle-power should be made at such a distance from the source of light that the latter may be regarded as practically a point. Where tests are made in the measurement of lamps with reflectors, the results should always be given as "apparent candle-power" at the distance employed, which distance should always be specifically stated.

886 **The output of all illuminants** should be expressed in lumens.

887 **Illuminants should be rated** upon a lumen basis instead of a candle-power basis.

888 **The specific output of electric lamps** should be stated in lumens per watt; and the specific output of illuminants depending upon combustion should be stated in lumens per b.t.u. per hour. The use of the term "efficiency" in this connection should be discouraged.

When auxiliary devices are necessarily employed in circuit with a lamp, the input should be taken to include both that in the lamp and that in the auxiliary devices. For example, the watts lost in the ballast resistance of an arc lamp are properly chargeable to the lamp.

889 **The Specific Consumption** of an electric lamp is its watt consumption per lumen. "Watts per candle" is a term used commercially in connection with electric incandescent lamps, and denotes, watts per mean horizontal candle-power.

890 **Life Tests. Electric Incandescent Lamps** of a given type may be assumed to operate under comparable conditions only when their lumens per watt consumed are the same. Life-test results, in order to be compared, must be either conducted under, or reduced to, comparable conditions of operation.

891 **In Comparing Different Luminous Sources,** not only should their candle-power be compared, but also their relative form, brightness, distribution of illumination and character of light.

892 **Lamp Accessories. A reflector** is an appliance, the chief use of which is to redirect the luminous flux of a lamp in a desired direction or directions.

893 **A Shade is** an appliance, the chief use of which is to diminish or to interrupt the flux of a lamp in certain directions, where such flux is not desirable. The function of a shade is commonly combined with that of a reflector.

894 **A Globe is** an enclosing appliance of clear or diffusing materials, the chief use of which is either to protect the lamp, or to diffuse its light.

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4 In case of a uniform point-source, this factor would be unity, and for a straight cylindrical filament obeying the cosine law it would be $\pi/4$.

895

TABLE XIX.

Photometric Units and Abbreviations.

Photometric quantity	Name of unit	Abbreviations, Symbols and defining equations
1. Luminous flux	Lumen	$F.\ \Psi$
2. Luminous intensity	Candle	$I = \frac{dF}{d\omega}, \Gamma = \frac{d\Psi}{d\omega}$, cp.
3. Illumination	Phot., foot-candle, lux	$E = \frac{dF}{dS} = \frac{I}{r^2}\cos\theta.\beta$
4. Exposure	Phot-second	$t\ \ E$
5. Brightness	Apparent candles per sq. cm.	$b = \frac{dI}{dS\ \cos\ \theta}$
	Apparent candles per sq. in.	
	Lambert	$L = \frac{dF}{dS}$
6. Normal brightness	Candles per sq. cm.	$b_0 = \frac{dI}{dS}$
	Candles per sq. in.	
7. Specific luminous radiation	Lumens per sq. cm.	
	Lumens per sq. in.	$E' = \pi b_0 \beta'$
8. Coefficient of reflection	—	$m = \frac{E'}{E}$

9. Mean spherical candlepower — scp
10. Mean lower hemispherical candlepower — lcp
11. Mean upper hemispherical candlepower — ucp
12. Mean zonal candlepower — zcp
13. 1 lumen is emitted by 0.07958 spherical cp.
14. 1 spherical candlepower emits 12.57 lumens.
15. 1 lux = 1 lumen incident per square meter = 0,0001 phot = 0.1 milliphot.
16. 1 phot = 1 lumen incident per sq. cm. = 10.000 lux = 1000 milliphot.
17. 1 milliphot = 0.001 phot = 0.929 foot-candle.
18. 1 foot-candle = 1 lumen incident per square foot = 1.076 milliphot = 10.76 lux.
19. 1 lambert = 1 lumen emitted per square centimeter.*
20. 1 millilambert = 0.001 lambert.
21. 1 lumen, emitted, per square foot* = 1.076 millilambert.
22. 1 millilambert = 0.929 lumen, emitted, per square foot*.
23. 1 lambert = 0.3183 candle per sq. cm. = 2.054 candles per sq. in.
24. 1 candle per sq. cm. = 3.1416 lamberts.
25. 1 candle per sq. in. = 0.4868 lamberts = 486.8 millilamberts.

*Perfect diffusion assumed.

SYMBOLS.

In view of the fact that the symbols heretofore proposed by this committee conflict in some cases with symbols adopted for electric units by the International Electrotechnical Commission, it is proposed that where the possibility of any confusion exists in the use of electrical and photometric symbols, an alternative system of symbols for photometric quantities should be employed. These should be derived exclusively from the Greek alphabet, for instance:

Luminous intensity.....Γ
Luminous flux.....Ψ
Illumination.....β

STANDARDS FOR TELEPHONY AND TELEGRAPHY

910 After careful consideration, it does not seem that the time is yet ripe for a formal standardization of terms and definitions used in telephony and telegraphy. Many of the terms commonly employed are used in more than a single way, and conversely, many pieces of apparatus and many constants which are essentially identical from a physical standpoint have been and are known by more than one designation.

911 **Damping of a Circuit.** The damping, at a given point, in a circuit from which the source of energy has been withdrawn, is the progressive diminution in the effective value of electromotive force and current at that point resulting from the withdrawal of electrical energy.

912 **Damping Constant.** The damping constant of a circuit depends upon the ratio of the dissipative to the reactive component of its impedance or admittance.

Applied to the admittance of a condenser or other simple circuit having capacity reactance, the damping constant for a harmonic electromotive force of given frequency is the ratio of the conductance of the condenser or simple circuit at that frequency, to twice the capacity of the condenser at the same frequency.

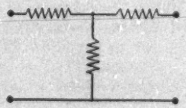
Applied to the reactance of a coil or other simple circuit having inductive reactance, the damping constant for a harmonic current of given frequency is the ratio of the resistance of the coil or circuit at that frequency, to twice the inductance at the same frequency.

913 **Equivalent Circuit.** An equivalent circuit is a simple network of series and shunt impedances, which, at a given frequency, is the approximate electrical equivalent of a complex network at the same frequency and under steady-state conditions.

NOTE: As ordinarily considered, the simple networks as defined, are the electrical equivalents of complex networks only with respect to definite pairs of terminals, and only as to sending-end impedances, and total attenuation. A further requirement is that the only connections between the pairs of terminals are those through the network itself.

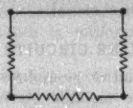
914 **"T" Equivalent Circuit.** A "T" equivalent circuit is a triple-star or "Y" connection of three impedances externally equivalent to a complex network.

Symbol:



915 **"U" Equivalent Circuit.** A "U" equivalent circuit is a delta connection of three impedances externally equivalent to a complex network. It is also called a "Π" equivalent circuit.

Symbol:



IMPEDANCE

916 **Mutual Impedance.** The mutual impedance, for alternating currents, between a pair of terminals and a second pair of terminals of a network, under any given condition, is the negative vector ratio of the electromotive force produced between either pair of terminals on open circuit, to the current flowing between the other pair of terminals.

917 **Self Impedance.** The self impedance between a pair of terminals of a network, under any given condition, is the vector ratio of the electromotive force applied across the terminals to the current produced between them.

LINE CHARACTERISTICS

918 **Characteristic Impedance.** The characteristic impedance of a line is the ratio of the applied electromotive force to the resulting steady-state current upon a line of infinite length and uniform structure, or of periodic recurrent structure.

NOTE: In telephone practice, the terms (1) line impedance, (2) surge impedance, (3) iterative impedance, (4) sending-end impedance, (5) initial sending-end impedance, (6) final sending-end impedance, (7) natural impedance and (8) free impedance, have apparently been more or less indefinitely and indiscriminately used as synonyms with what is here defined as "characteristic impedance."

919 **Sending-End Impedance.** The sending-end impedance of a line is the vector ratio of the applied electromotive force to the resulting steady-state current at the point where the electromotive force is applied.

NOTE: See note under "Characteristic Impedance." In case the line is of infinite length of uniform structure or of periodic recurrent structure, the sending-end impedance and the characteristic impedance are the same.

920 **Propagation Constant.** The propagation constant per unit length of a uniform line, or per section of a line of periodic recurrent structure, is the natural logarithm of the vector ratio of the steady-state currents at various points separated by unit length in a uniform line of infinite length, or at successive corresponding points in a line of recurrent structure of infinite length. The ratio is determined by dividing the value of the current at the point nearer the transmitting end by the value of the current at the point more remote.

921 Attenuation Constant. The attenuation constant is the real part of the propagation constant.

922 Wave-Length Constant. The wave-length constant is the imaginary part of the propagation constant.

LINE CIRCUITS

930 Ground-Return Circuit. A ground-return circuit is a circuit consisting of one or more metallic conductors in parallel, with the circuit completed through the earth.

931 Metallic Circuit. A metallic circuit is a circuit of which the earth forms no part.

932 Two-Wire Circuit. A two-wire circuit is a metallic circuit formed by two paralleling conductors insulated from each other.

933 Superposed Circuit. A superposed circuit is an additional circuit obtained from a circuit normally required for another service, and in such a manner that the two services can be given simultaneously without mutual interference.

934 Phantom Circuit. A phantom circuit is a superposed circuit, each side of which consists of the two conductors of a two-wire circuit in parallel.

935 Side Circuit. A side circuit is a two-wire circuit forming one side of a phantom circuit.

936 Non-Phantomed Circuit. A non-phantomed circuit is a two-wire circuit, which is not arranged for use as the side of a phantom circuit.

937 Simplexed Circuit. A simplexed circuit is a two-wire telephone circuit, arranged for the super-position of a single ground-return signalling circuit-operating over the wires in parallel.

NOTE: In view of the use of the term "Simplex Operation" in telegraph practice, it is felt that the designation "Simplexed Circuit" as applied to the arrangement described is not a happy one.

938 Composited Circuit. A composited circuit is a two-wire telephone circuit, arranged for the superposition on each of its component metallic conductors, of a single independent ground-return signalling circuit.

939 Quadded or Phantomed Cable. A quadded or phantomed cable is a cable adapted for the use of phantom circuits.

NOTE: The type of cable here defined has frequently been designated as "Duplex Cable"—a term which is objectionable, both on account of its lack of description and its widely different use in telegraph practice.

LOADING

950 Loaded Line. A loaded line is one in which the normal inductance of the circuit has been altered for the purpose of increasing its transmission efficiency for one or more frequencies.

951 Series Loaded Line. A series loaded line is one in which the normal inductance has been altered by inductance serially applied.

952 **Shunt Loaded Line.** A shunt loaded line is one in which the normal inductance of the circuit has been altered by inductance applied in shunt across the circuit.

953 **Continuous Loading.** A continuous loading is a series loading in which the added inductance is uniformly distributed along the conductors.

954 **Coil Loading.** A coil loading is one in which the normal inductance is altered by the insertion of lumped inductance in the circuit at intervals. This lumped inductance may be applied either in series or in shunt.

NOTE: As commonly understood, coil loading is a series loading, in which the lumped inductance is applied at uniformly spaced recurring intervals

955 **Microphone.** A contact device designed to have its electrical resistance directly and materially altered by slight differences in mechanical pressure.

956 **Relay.** A relay is a device by means of which contacts in one circuit are operated under the control of electrical energy in the same or other circuits.

957 **Resonance.** Resonance of a harmonic alternating current of given frequency, in a simple series circuit, containing resistance, inductance and capacity, is the condition in which the positive reactance of the inductance is numerically equal to the negative reactance of the capacity. Under these conditions, the current flow in the circuit with a given electromotive force is a maximum.

958 **Retardation Coil.** A retardation coil is a reactor (reactance coil) used in a circuit for the purpose of selectively reacting on currents which vary at different rates.

NOTE: In telephone and telegraph usage, the terms "impedance coil," "inductance coil," choke coil" and "reactance coil" are sometimes used in place of the term "retardation coil."

959 **Skin Effect.** Skin effect is the phenomenon of the non-uniform distribution of current throughout the cross-section of a linear conductor, occasioned by variations in the intensity of the magnetic field due to the current in the conductor.

960 **Telephone Receiver.** A telephone receiver is an electrically operated device, designed to produce sound waves or vibrations which correspond in form to the electromagnetic waves or vibrations actuating it.

961 **Telephone Transmitter.** A telephone transmitter is a sound-wave or vibration-operated device designed to produce electromagnetic waves or vibrations which correspond in form to the sound waves or vibrations actuating it.

962 **The Coefficient of Coupling of a Transformer.** The coefficient of coupling of a transformer at a given frequency, is the vector ratio of the mutual impedance between the primary and secondary of the transformer, to the square root of the product of the self-impedances of the primary and of the secondary.

963 **Repeating Coil.** A term used in telephone practice meaning the same as transformer, and ordinarily a transformer of unity ratio.

APPENDIX I.

STANDARDS FOR RADIO COMMUNICATION

The following Sections **1000** to **1033** have been prepared by the Standardization Committee of the Institute of Radio Engineers, and are here included by permission as an Appendix, until further revised.

1000 Acoustic Resonance Device. One which utilizes, in its operation, resonance to the audio frequency of the received impulses.

1001 Antenna. A system of conductors designed for radiating or absorbing the energy of electromagnetic waves.

1002 Atmospheric Absorption. That portion of the total loss of radiated energy due to atmospheric conductivity.

1003 Audio Frequencies. The normally audible frequencies lying below 20,000 cycles per second (see also radio frequencies).

1004 Capacitive Coupler. An apparatus which, by electric fields, joins portions of two radio frequency circuits and is used to transfer electrical energy between these circuits through the action of electric forces.

1005 Coefficient of Coupling (Inductive). The ratio of the effective mutual inductance of two circuits to the square root of the product of the effective self-inductances of each of these circuits.

1006 Direct Coupler. An apparatus which magnetically joins two circuits having a common conductive portion and which is used to transfer electrical energy between these circuits.

1007 Counterpoise. A system of electrical conductors insulated from ground forming one plate of a condenser, the other plate of which is the antenna. In land stations a counterpoise forms a capacitive connection to ground.

1008 A Damped Alternating Current is a current which alternates regularly in direction and whose amplitude progressively diminishes.

1009 The Damping Factor of an exponentially damped alternating current is the product of the logarithmic decrement and the frequency.

Let I_0 = initial amplitude

I_t = amplitude at the time t

ϵ = base of Napierian logarithms

a = damping factor

Then: $I_t = I_0\, \epsilon^{-at}$

1010 Detector. That portion of the receiving apparatus which, connected to a circuit carrying currents of radio frequency, and in conjunction with a self-contained or separate indicator, translates the radio frequency energy into a form suitable for operation of

the indicator. This translation may be effected either by the conversion of the radio frequency energy, or by means of the control of local energy by the energy received.

1011 Electromagnetic Wave. A progressive disturbance characterized by the existence on the wave front of electric and magnetic forces acting in directions which are perpendicular to each other and to the direction of propagation of the wave.

1012 Forced Alternating Current. A current produced in any circuit by the application of an alternating electromotive force.

1013 Free Alternating Current. A current produced by means of an electromagnetic disturbance in a circuit, having capacity, inductance, and *less* than the critical resistance.

1014 Critical Resistance of a Circuit determines the limit between the oscillatory and aperiodic discharge of that circuit. (The discharge is aperiodic if the circuit resistance is greater than the critical value and is alternating when the resistance is less than the critical value). In a circuit without dielectric or magnetic hysteresis, the critical resistance equals $2\sqrt{\frac{L}{C}}$, where L and C are the effective inductance and capacity of the circuit.

1015 Group Frequency. The number per second of periodic changes in amplitude or frequency of an alternating current.

NOTE 1. Where there is more than one periodic recurrent change of amplitude or frequency, there is more than one group frequency present.

NOTE 2. The term "group frequency" replaces the term "spark frequency."

1016 Inductive Coupler. An apparatus which, by magnetic forces, joins portions of two radio frequency circuits and is used to transfer electrical energy between these circuits, through the action of magnetic forces.

1017 Linear Decrement of a Linearly Damped Alternating Current is the difference of successive current amplitudes in the same direction, divided by the larger of these amplitudes.

Let: I_n and I_{n+1} be successive current amplitudes in the same direction, of a linearly-damped alternating current.

Then: The linear decrement, $b = \frac{I_n - I_{n+1}}{I_n}$

Also: $I_t = I_0\,(1 - bft)$

Where: I_0 = initial current amplitude

I_t = current amplitude at time t

f = frequency of alternating current

1018 Logarithmic Decrement of an exponentially damped alternating current is the logarithm of the ratio of successive current amplitudes in the same direction.

NOTE: Logarithmic decrements are standard for a complete period or cycle.

Let: I_n and I_{n+1} be successive current amplitudes in the same direction.

$$d = \text{logarithmic decrement}$$

Then: $$d = \log_e \frac{I_n}{I_{n+1}}$$

1019 Radio Frequencies. Those above 20,000 cycles per second (see also Audio Frequencies).

NOTE: It is not implied that radiation cannot be secured at lower frequencies and the distinction from audio frequencies is merely one of definition based on convenience.

1020 Resonance to an Exciting Alternating Current of a given frequency in an oscillating circuit is that condition in which the resulting effective current (or voltage) in that circuit is a maximum.

If neither the free nor the forced alternating currents of the driven circuit are highly damped, then resonance is obtained when the frequency of the free alternating current is approximately equal to the frequency of the forced alternating current.

That is, $$\omega = \frac{1}{\sqrt{LC}} = \omega_1$$

Where: ω = $2\pi \times$ the frequency of the free alternating current in the circuit.
L = the effective inductance of the circuit.
C = the effective capacity of the circuit.
ω_1 = angular velocity of the forced alternating current.

This is equivalent to the condition $\omega L = \frac{1}{\omega C}$ *i.e.*, the inductive reactance at that frequency is numerically equal to the capacitive reactance, or that the total reactance $\left(\omega L - \frac{1}{\omega C}\right)$ is equal to 0.

1021 A Resonance Curve gives the power, current, or voltage at various frequencies of excitation, as a function of those frequencies. or of the corresponding wave lengths.

1022 A Wave-Length Resonance Curve is one wherein the abscissas are ratios of specified wave lengths to the resonant wave length, and the ordinates are ratios of the energy (or square of the current) at corresponding specified wave lengths to the energy (or square of the current) at the resonant wave length. It is advantageous to have the scales of ordinates and abscissas equal.

1023 A Frequency Resonance Curve. One wherein the abscissas are ratios of specified frequencies to the resonant frequency, and the ordinates are ratios of the energy (or square of the current) at corresponding specified frequencies to the energy (or square of the current) at the resonant frequency. The scales of ordinates and abscissas are equal.

1024 A Standard Resonance Curve, unless otherwise specified, is assumed to be a wave-length resonance curve.

1025 Selecting. The process of adjusting an element driven by a plurality of simultaneous impulses, until the ratio of desired response to undesired response is a maximum.

1026 Sustained Radiation consists of electromagnetic waves of constant amplitude (such as are emitted from an antenna in which a forced alternating current flows.)

1027 Tuning. The process of securing the maximum indications by adjusting the time period of a driven element. (In transmitter or receiver.)

1028 A Wave-Length Meter, commonly called a **Wave-Meter,** is a radio frequency measuring instrument, calibrated to read wave lengths.

1029 Rating. 1. All radio transmitting sets shall be rated in actual power output measured in the antenna.

NOTE: The group or audio frequency of the note of the station should be stated as well, (except for sustained wave sets, where that characteristic should be mentioned).

2. The over-all efficiency of a radio transmitting station shall be the ratio of the actual power output as measured in the antenna to the power input supplied to the first piece of electrical machinery which is definitely a part of the radio equipment.

1030 Decremeter. An instrument for measuring the logarithmic decrement of a circuit or of a train of electromagnetic waves.

1031 Attenuation, Radio. The decrease with distance from the radiating source, of the amplitude of the electric and magnetic forces accompanying (and constituting) an electromagnetic wave.

1032 Attenuation Coefficient (Radio). The coefficient, which, when multiplied by the distance of transmission through a uniform medium, gives the natural logarithm of the ratio of the amplitude of the electric or magnetic forces at that distance, to the initial value of the corresponding quantities.

1033 Coupler. An apparatus which is used to transfer radio-frequency energy from one circuit to another by associating portions of these circuits.

APPENDIX II.

ADDITIONAL STANDARDS FOR RAILWAY MOTORS

1100 In comparing projected motors, and in case it is not possible or desirable to make tests to determine mechanical losses, the following values of these losses, determined from the averages of many tests over a wide range of sizes of single-reduction single-geared motors, will be found useful, as approximations. They include axle-bearing, gear, armature-bearing, brush-friction, windage, and stray-load losses.

TABLE XX
Approximate Losses in D-C. Railway Motors.

Input in per cent of that at nominal rating	Losses as per cent of input
100 or over	5.0
75	5.0
60	5.3
50	6.5
40	8.8
30	13.3
25	17.0

1101 The core loss of railway motors is sometimes determined by separately exciting the field, and driving the armature of the motor to be tested, by a separate motor having known losses and noting the differences in losses between driving the motor light at various speeds and driving it with various field excitations.

1102 Selection of Motor For Specified Service

The following information relative to the service to be performed, is required, in order that an appropriate motor may be selected.

(a) Weight of total number of cars in train (in tons of 2000 lb.) exclusive of electrical equipment and load.
(b) Average weight of load and durations of same, and maximum weight of load and durations of same.
(c) Number of motor cars or locomotives in train, and number of trailer cars in train.
(d) Diameter of driving wheels.
(e) Weight on driving wheels, exclusive of electrical equipment.
(f) Number of motors per motor car.
(g) Voltage at train with power on the motors—average, maximum and minimum.

(h) Rate of acceleration in mi. per. hr. per second.
(i) Rate of braking (retardation in m. per hr. per second).
(j) Speed limitations, if any (including slowdowns).
(k) Distances between stations.
(l) Duration of station stops.
(m) Schedule speed including station stops in m.p.h.
(n) Train resistance in pounds per ton of 2000 pounds at stated speeds.
(o) Moment of inertia of revolving parts, exclusive of electrical equipment.
(p) Profile and alignment of track.
(q) Distance coasted as a per cent of the distance between station stops.
(r) Time of layover at end of run, if any.

1103 Stand-Test Method of Comparing Motor Capacity with Service Requirements: When it is not convenient to test motors under actual specific service conditions, recourse may be had to the following method of determining temperature rise.

1104 The essential motor losses affecting temperatures in service are those in the motor windings, core and commutator. The mean service conditions may be expressed, as a close approximation, in terms of that continuous current and core loss which will produce the same losses and distribution of losses as the average in service.

A stand test with the current and voltage which will give losses equal to those in service, will determine whether the motor has sufficient capacity to meet the service requirements. In service, the temperature rise of an enclosed motor (**§164**), well exposed to the draught of air incident to a moving car or locomotive, will be from 75 to 90 per cent (depending upon the character of the service) of the temperature rise obtained on a stand test with the motor completely enclosed and with the same losses. With a ventilated motor (**§165** and **§167**), the temperature rise in service will be 90 to 100 per cent of the temperature rise obtained on a stand test with the same losses.

1105 In making a stand test to determine the temperature rise in a specific service, it is essential in the case of a self-ventilated motor (**§ 167**), to run the armature at a speed which corresponds to the schedule speed in service. In order to obtain this speed it may be necessary, while maintaining the same total armature losses, to change somewhat the ratio between the I^2R and core-loss components.

1106 Calculation for Comparing Motor Capacity with Service Requirements. The heating of a motor should be determined, wherever possible, by testing it in service, or with an equivalent duty cycle. When the service or equivalent duty-cycle tests are not practicable, the ratings of the motor may be utilized as follows to determine its temperature rise.

1107 The motor losses which affect the heating of the windings are as stated above, those in the windings and in the core. The former are proportional to the square of the current. The latter vary with

the voltage and current, according to curves which can be supplied by the manufacturers. The procedure is therefore as follows:

1108 (a) Plot a time-current curve, a time-voltage curve, and a time-core loss curve for the duty cycle which the motor is to perform, and calculate from these the root-mean-square current and the equivalent voltage which, with this r.m.s. current, will produce the average core loss.

1109 (b) If the calculated r.m.s. service current exceeds the continuous rating, when run with average service core loss and speed, the motor is not sufficiently powerful for the duty cycle contemplated.

1110 (c) If the calculated r.m.s. service current does not exceed the continuous rating, when run with average service core loss and speed, the motor is ordinarily suitable for the service. In some cases, however, it may not have sufficient thermal capacity to avoid excessive temperature rises during the periods of heavy load. In such cases a further calculation is required, the first step of which is to calculate the temperature rise due to the r.m.s. service current, and equivalent voltage.

Let t = temperature rise
$p_0 = I^2R$ loss, kw.
p_c = core loss, kw.
} with r.m.s. service current, and equivalent service voltage.

T = temperature rise
$P_0 = I^2R$ loss, kw.
P_c = core loss, kw.
} with continuous load current corresponding to the equivalent service voltage.

Then

$$t = T\,\frac{p_0 + p_c}{P_0 + P_c}\text{, approximately.}$$

1111 (d) The thermal capacity of a motor is approximately measured by the ratio of the electrical loss in kw. at its nominal (one-hour) capacity, to the corresponding maximum observable temperature rise during a one hour test starting at ambient temperature.

1112 (e) Consider any period of peak load and determine the electrical losses in kilowatt-hours during that period from the *electrical* efficiency curve. Find the excess of the above losses over the losses with r.m.s. service current and equivalent voltage. The excess loss, divided by the co-efficient of thermal capacity, will equal the extra temperature rise due to the peak load. This temperature rise added to that due to the r.m.s. service current, and equivalent voltage, gives the total temperature rise. If the total temperature rise in any such period exceeds the safe limit, the motor is not sufficiently powerful for the service.

1113 (f) If the temperature reached, due to the peak loads, does not exceed the safe limit, the motor may yet be unsuitable for the service, as the peak loads may cause excessive sparking and dangerous mechanical stresses. It is, therefore, necessary to compare the peak loads with the short-period overload capacity. If the peaks are also within the capacity of the motor, it may be considered suitable for the given duty cycle.

APPENDIX III.

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INDEX

A

Section

Abbreviations 90
Acoustic Resonance Device 1000
Active Component of Current or Voltage 21
Acyclic Machine 141
Adjustable-Speed Motors 153
Alternating-Current Apparatus, Efficiency of 430
Alternating Current defined 1012, 1013, 4
Alternating-Current Commutating Machines 131
Alternating Current, Forced 1012
Alternating Current ,Free 1013
Alternator 134
Alternators, Variation in 66
Altitude, correction for 308
Ambient Temperature 303
Ambient Temperature of Reference for Air 305
Ambient Temperature of Reference for Water 309
Ammeter 225
Angular Displacement of e.m.fs between transformers 609
Angular Velocity 9
Antenna 1001
Anti-inductive Load 25
Apparent Power 27
Assurance, Factor of 681
Atmospheric Absorption 1002
Attenuation Constant 921
Audio Frequencies 1003
Auto-Transformer 209
Auxiliary Apparatus, Losses in 457
Auxiliary Machine Rating 277

B

Balancer 106
Barometric Pressure for Institute Rating 265
Bearing Friction and Windage 450
Booster 103
Bracket Systems 785
Bridge Systems 786
Brightness 861
Brightness, Normal 862
Brush Contact Loss 454
Brush Friction 451

C

Cable 638
Cable, Concentric-Lay 643
Cable, Concentric, N-Conductor 646
Cable, Duplex 647
Cable, N-Conductor 645
Cable, Rope-Lay 644
Cable, Triplex 649
Cable, Twin 648
Cables, Breakdown Tests of 686

Section
Cables, Capacitance of Electric Light and Power.... 698
Cables, Electrical Tests of.... 678
Cables, Heating of.... 677
Cables, Insulation Resistance of.... 688
Cables, Insulation Resistance Tests of.... 692
Cables, Measurement of Capacitance of.... 696
Cables, Multiple Conductor, Capacity of.... 698
Cables, Multiple Conductor, Insulation Tests of.... 693
Cables, Multiple Conductor, Tests of.... 687
Cables, Paired.... 697
Cables, Safe Limiting Temperature of.... 677
Cables, Sectional Area of.... 654
Cables, Test Voltage and Frequency.... 683
Cables, Test Voltage of.... 682
Candle Power.... 856
Capacitance.... 80, 694
Capacitance, Measurement of.... 696
Capacity.... 80, 252
Capacitive Coupler.... 1004
Capacity of Electrical Machines.... 261, 800
Cascade Converter.... 111
Catenary, Compound.... 781
Catenary, Simple.... 781
Catenary Suspension.... 781
Center Contact Rail.... 770
Circuit Breakers, Definition.... 724
Circuit Breakers, Performance and Test.... 726
Circuit Breakers, Rating of.... 725
Circuits.... 930
Characteristic Curve of Luminous Sources.... 877
Characteristic Impedance.... 918
Classification of Machinery.... 100
Classification of Machines for Enclosure.... 160
Coil Loading.... 954
Collector Rings, Temperature of.... 389
Commutating A-C Machines, Losses of.... 443
Commutating Machines.... 130
Commutation Requirements.... 402
Commutators, Temperature of.... 390
Comparison Lamp.... 874
Composited Circuit.... 938
Concentric-Lay Cable.... 643
Concentric Strand.... 642
Condensive Load.... 25
Conductivity of Copper.... 675
Conductor and Rail Systems.... 766
Conductor, Contact.... 766
Conductor Defined.... 636
Conductor, Stranded.... 637
Conductors, Sizes of.... 652
Connected Load.... 61
Connections of Transformers.... 606
Constant-Current Machines, Regulation of.... 563
Constant-Speed D-C. Motor, Regulation of.... 564
Constant-Speed Motors.... 151
Contact Conductors.... 766
Contact Rail.... 767
Contact Rail, Center.... 770
Contact Rail, Overhead.... 768
Contact Rail, Underground.... 771
Contact Voltage Regulator.... 211
Continuous Current defined.... 3

Section
Continuous Loading 953
Continuous Rating 281
Conventional Efficiency 423
Converter 108
Copper, Conductivity of 675
Copper Wire Tables 676
Cord 641
Core Loss at No Load 452, 818, 1101
Cores 391
Corrections for Deviation of Ambient Temperature 320
Correction for Lay 656
Counter-clockwise Convention 20
Counterpoise 1007
Coupling Coefficient 962
Crest Voltage Meter 227
Crest Factor 15
Critical Resistance 1014
Cross-Span Systems 783
Cross-Span Systems, Messenger 784
Current Capacity 80
Current Ratio of Transformer 206
Cycle 6

D

Damping 911, 1008
Damping Constant 912
Damping Factor 1009
Definitions ..... 1 to 83
Demand 57
Demand Factor 59
Detector 1010
Dielectric Tests 480
Dielectric Tests of Cables 680
Direct Coupler 1006
Direct-Current Commutating Machines 130
Direct Current Compensator 106
Direct-Current Converter 109
Direct Current defined 1
Direct-Current Machines, Losses of 440
Direct Suspension 780
Distortion Factor 17
Distribution System 761
Diversity Factor 60
Double-Current Generator 107
Drip-proof Machine 168
Duplex Cable 647
Duration of Heat Run 322, 324
Duty-Cycle Operation 284
Dynamotor 105

E

Effective Value 10
Efficiency 83
Efficiency and Losses 420
Efficiency as affected by Wave-Shape 431
Efficiency, Conventional 423
Efficiency Determination 423, 426
Efficiency, Measurement of 428
Efficiency, Plant 421
Efficiency with Reference to Temperature 432
Electric Locomotives 830
Electric Railways, Standards for 760
Electrical Degree 7
Embedded Temperature Detector Method 352

Section
Electro-Magnetic Wave....1011
Enclosed Machine.... 164
Equivalent Circuit.... 913
Equivalent Phase Difference.... 29
Equivalent Sine Wave.... 18
Equivalent Tests, Standard Duration of.... 285
Explosion-Proof Machine.... 171
Exposure.... 859

F

Factor of Assurance.... 681
Field-Rheostat Loss.... 455
Flexible Stranding.... 655
Fluctuation.... 569
Form Factor.... 16
Frequency.... 9
Frequency Converter.... 112
Frequency, Resonance Curve....1023
Fuses, Definition.... 729
Fuses, Rating of.... 730
Fuses, Temperature of.... 731
Fuses, Test of.... 732

G

Gage of Third Rail.... 772
Generator.... 101
Generator, Double-Current.... 107
Generators, Regulation of.... 561, 562
Ground-Return Circuit.... 930
Group Frequency....1015

H

Heating and Temperature.... 300
High-voltage winding.... 202
Hottest Spot Correction.... 346
Hottest Spot Temperature Table.... 376
Hydraulic Turbine, Regulation of.... 570

I

Illumination.... 854
Illumination and Photometry.... 850
Impedance, Characteristic.... 918
Impedance Drop, per cent.... 52
Impedance, Mutual.... 916
Impedance, Self.... 917
Impedance, Sending-End.... 919
Incandescent Lamps, Rating of.... 886
Induction Apparatus, Stationary.... 200
Induction Generator.... 140
Induction Machines.... 138
Induction Machines, Losses of.... 442
Induction Machines, Stray-Load Losses of.... 459
Induction Motor.... 139
Induction Motor Rotor Loss.... 460
Induction Voltage Regulator.... 212
Inductive Coupler....1016
Inductive Load.... 25
Inductor Alternator.... 136
Information on Rating Plate.... 620
In-phase Component of Current or Voltage.... 21
Instrument Transformers.... 741
Insulation Resistance of Machinery.... 550

K

Section
Kilovolt-ampere Rating 275
Kilowatt Rating 274, 276
Kinds of Rating 281

L

Lag 19
Lay, Correction for 656
Lead 19
Leads of Transformers, Marking of 600
Life Tests of Lamps 890
Lightning Arresters Definition 733
Lightning Arresters, Performance and Test 735
Lightning Arresters, Rating of 734
Line Characteristics 918
Line Circuits, Telephone and Telegraph ..... 930 to 939
Line-Drop Voltmeter Compensator 231
Linear Capacitance 694
Linear Decrement 1017
Linear Insulation Resistance 890
Load Factor 55
Loaded Line 950
Loading 950
Locomotives, Electric 830
Logarithmic Decrement 1018
Loss, Brush-Contact 454
Losses, Evaluation of 436
Losses in Auxiliary Apparatus 457
Losses in Constant-Potential Machinery 4 33
Losses in Field Rheostats 455
Losses in Transformers 470
Losses, Stray Load 434
Losses, Table of 435
Losses to Consider in Various Machines 440
Low-voltage Winding 202
Lumen 857
Luminous Flux 850
Luminous Intensity 853
Luminous Standard, Primary 870
Luminous Standard, Representative 871
Lux 858

M

Machine Efficiency 420
Machinery Cooled by Ventilating Air from Distance 304
Machinery Exposed to Sun's Rays 313
Magnetic Degree 64
Magneto Voltage Regulator 213
Marked Ratio of Instrument Transformer 207
Maximum Demand 58
Mean Hemispherical Candle-power 882
Mean Horizontal Candle-Power 880
Mean Spherical Candle-Power 881
Mean Zonal Candle-Power 883
Measurement of Ambient Temperature 314
Mechanical Degree 64
Megohms Constant 691
Messenger Suspension 781
Messenger Wire or Cable 778
Metallic Circuits 931
Microfarads, Constant 795
Microphone 955
Milliphot 858
Moisture-Resisting Machine 169

Section

Motor 102
Motor Converter 111
Motor-Booster 103
Motor Generator 104
Motors, Speed Classification of 150
Motors, Stalling Torque of 404
Multi-Speed Motors 152
Mutual Impedance 16

N

N-Conductor Cable 645
Needle-Point Spark-Over Voltages 537
Nominal Rating 283, 415
Non-Inductive Load 25
Non-Phantomed Circuit 936
Non-sinusoidal quantities 14
Notation 90

O

Object of Standardization 260
Oil Temperature 385
Open Machine 161
Oscillating Current 5, 551
Over Speeds ..... 399 to 401
Overhead Construction 779
Overhead Contact Rail 768

P

Pair, Twisted 650
Paired Cables 697
Peak Factor 15
Per-cent Drop 50
Percentage Saturation 63
Performance Curve 876
Period 8
Π Equivalent Circuit 915
Phantomed Cable 939
Phantom Circuit 934
Phase 13
Phase Advancer 114
Phase Difference 19
Phase-Modifier 114
Phot 858
Photometric Tests 885
Plant Efficiency 421
Plant Factor 56
Polyphase 34
Polyphase Alternator 135
Power Capacity 80
Power-Factor 28
Power in A-C. Circuits 26
Primary Winding 202
Prime Movers, Fluctuation of 569
Prime Movers, Pulsation in 68
Prime Movers, Regulation of 568
Prime Movers, Variation in 65
Propagation Constant 920
Protected Machine 162
Protective Reactors, Definition 736
Protective Reactors, Performance and Tests 738
Protective Reactors, Rating 737
Pulsating Current Defined 2
Pulsation 68

Q

Section

Quadded Cable.... 939
Quadrature Component of Current or Voltage.... 22
Quarter-phase.... 32

R

Radio Communication.... 1000
Radio Frequencies.... 1019
Radio Transmitting Sets, Rating of.... 1029
Rail, Contact.... 767
Rail, Third.... 769
Railway Motor, Selection of.... 1102
Railway Motor, Standard Tests of.... 1103
Railway Motors.... 415, 800 to 820
Railway Motors, Capacity and Requirements of.... 1106
Railway Motors, Efficiency and Losses of.... 815
Railway Motors, Characteristic Curves of.... 810
Railway Motors, Continuous Rating of.... 802
Railway Motors, Maximum Input of.... 803
Railway Motors, Temperature Limitations of.... 804
Rated Current of Constant Potential Transformer.... 203
Rating, Continuous.... 281
Rating in Kilowatts.... 274, 276
Rating, Nominal.... 283
Rating of Electrical Machines.... 262
Rating of Incandescent Lamps.... 886
Rating Plate, Information on.... 620 to 630
Rating, Short Time.... 282
Ratio of Transformer.... 204
Reactance Drop, Per Cent.... 51
Reactive Component of Current or Voltage.... 22
Reactive Factor.... 23
Reactive Volt-Amperes.... 24
Reactor.... 56, 82, 214
Recording Instruments.... 124, 229
Reduction Factor, Spherical.... 884
Reference Standard.... 872
Reflection Coefficient.... 866
Reflection, Coefficient of Diffuse.... 868
Reflection, Coefficient of Regular.... 867
Regulation.... 279, 560
Regulation and Excitation.... 294, 583
Regulation and Frequency.... 291, 580
Regulation and Power-Factor.... 292, 581
Regulation and Wave Form.... 292, 582
Regulation of A-C. Generators.... 297, 295, 584, 586
Regulation Tests.... 291, 580
Relay.... 956
Repeating Coil.... 363
Resistance Drop, Per Cent.... 35, 50
Resistance Method of Measuring Temperature.... 177, 348
Resistor.... 55, 81, 740
Resonance.... 957
Resonance Curve.... 1021
Retardation Coil.... 958
Rope-Lay Cable.... 644
Root-Mean-Square.... 10
Rotary Phase-Converter.... 113
Rotating Machines.... 101

S

Saturation Factor.... 62
Secondary Winding.... 202
Selecting.... 1025

Section
Self Impedance.... 915
Self-ventilated Machine.... 167
Semi-enclosed Machine.... 164
Sending-End Impedance.... 919
Separately Ventilated Machines.... 165
Short-Time Rating.... 282
Short-Circuit Stresses.... 398
Side Circuit.... 955
Simple Alternating Current.... 12
Simplexed Circuit.... 957
Single-Phase.... 30
Sinusoidal Current.... 12
Six-phase.... 33
Skin Effect.... 959
Spark Gap Measurements.... 530, 534
Spark Gap, Needle.... 536
Spark Gap, Sphere.... 538
Sparking Distance, Needle.... 537
Special Temperature Limits.... 385
Specific Consumption.... 889
Specific Luminous Radiation.... 860
Specific Output of Lamps.... 888
Speed Classification of Motors.... 150
Sphere Spark Gap.... 538
Spherical Reduction Factor.... 884
Squirrel Cage Windings, Temperature of.... 388
Stalling Torque of Motors.... 404
Standard Durations of Equivalent Tests.... 285
Standard Resonance Curve.... 1024
Standard Temperature for Institute Rating.... 265
Standard, Working (Photometric).... 873
Standards for Electrical Machinery.... 250
Stationary Induction Apparatus.... 200
Steam Engines, Regulation of.... 568
Strand.... 639
Strand, Concentric.... 642
Stranded Conductor.... 637
Stranded Wire.... 640
Stranding.... 653
Stranding, Flexible.... 655
Stray Load Losses.... 434
Substation, Definition.... 762
Substation Machinery Rating.... 763
Submersible Machine.... 170
Superposed Circuit.... 932
Supporting Systems.... 782
Suspension, Direct.... 780
Sustained Radiation.... 1026
Switches, Definition.... 721
Switches, Performance and Tests of.... 723
Switches, Rating of.... 722
Symbols.... 90
Symbols, Photometric.... 896
Synchroscope.... 232
Synchronoscope.... 232
Synchronous Commutating Machines.... 132
Synchronous Condenser.... 115
Synchronous Converter.... 110
Synchronous Converters, Losses of.... 444
Synchronous Machines.... 133
Synchronous Machines, Losses of.... 441

Section

Synchronous Machines, Stray-Load Losses..... 458
Synchronous Motor..... 137
Synchronous Phase-Modifier..... 115

T

Tables of Copper Wire..... 676
Telephone Receiver..... 960
Telephone Transmitter..... 961
Telephony and Telegraphy..... 910
Temperature, Ambient..... 303
Temperature Detectors..... 354
Temperature Elevations, Table of..... 379
Temperature Limitations..... 300
Temperature Limits..... 375
Temperature Measurements..... 340
Temperature of Transformer Winding..... 351
Temperatures in Centigrade..... 251
T Equivalent Circuit..... 914
Test Lamp..... 875
Test Voltage for Cables..... 682
Test Voltage, Measurement of..... 530, 540
Test Voltages, Conditions for..... 481
Test Voltages, Duration of..... 485
Test Voltages for Machines..... 480
Test Voltages, Frequency and Wave Form..... 484
Test Voltages, Values of and Exceptions..... 500, 512
Thermometer Method of Measuring Temperature..... 345, 347
Third Rail..... 769
Third Rail, Elevation of..... 773
Third Rail, Gage of..... 772
Third Rail, Protection..... 776
Third Rail, Standard Elevation of..... 775
Third Rail, Standard Gage of..... 774
Three-Phase..... 31
Three-Phase Transformers, Marking Leads of..... 607
Tractive Effort..... 832, 833
Transformer Connections..... 600
Transformer, Ratio of..... 204, 207
Transformers..... 201
Transformers, Angular Displacement between..... 608
Transformers, Constant Potential, Regulation of..... 565
Transformers, Loading-Back Tests..... 394
Transformers, Loading for Temperature Tests..... 393
Transformers, Losses of..... 445
Transformers, No-Load Losses..... 470
Transformers, Parallel Operation of..... 610
Transformers, Reactance Drop..... 587
Transformers, Regulation of..... 587
Transformers, Stray-Load Losses..... 471
Transformers, Volt-Ampere Ratio..... 203
Transmission Lines, Regulation of..... 567
Transmission System..... 760
Triplex Cable..... 649
Trolley Wire..... 777
Trolley Wire Height, Standard..... 787
Tuning..... 1027
Twin Cable..... 648
Twin Wire..... 651
Twisted Pair..... 650
Two-phase..... 32
Two-Wire Circuit..... 932

U

Section
U Equivalent Circuit..... 915
Underground Contact Rail..... 771
Unipolar Machines..... 147
Units in which Rating shall be expressed..... 274 to 277

V

Variation..... 65, 66
Varying-Speed Motors..... 154
Ventilating Blower..... 456
Virtual..... 10
Voltage Ratio of Transformer..... 205
Voltage Regulator..... 210
Voltage Tests, Conditions for..... 481
Volt-amperes..... 27
Voltmeter..... 236

W

Water-Cooled Machine..... 166
Water-Cooled Transformers..... 310
Water-Cooled Transformers, Temperature of..... 386
Watt-hour Meter..... 230
Wattmeter..... 228
Wave Form..... 11, 405
Wave-Form Deviation..... 406
Wave Length, Resonance Curve..... 1022
Weight on Drivers..... 831
Windage..... 450
Wire or Cable, Messenger..... 778
Wave-Length..... 912
Wave-Length Meter..... 1028
Wire, Copper, Tables of..... 676
Wire, Stranded..... 640
Wire, Trolley..... 777
Wire, Twin..... 651
Wires and Cables..... 635

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

REPORT OF THE BOARD OF DIRECTORS FOR FISCAL YEAR ENDING APRIL 30, 1914

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its annual report for the fiscal year ending April 30, 1914.

Only a summary of the work which has been accomplished during the year is possible in this report, but in the preparation of it a sufficient amount of detail has been given to convey a general idea of the scope and activity of the Institute. Those members desiring further information are referred to past issues of the monthly PROCEEDINGS, in which nearly all matters of importance have been given publicity in greater detail. Abstracts of the reports of many of the Institute committees, as submitted to the Board, are included herein.

The exact status of the Institute's financial affairs will be found in the statements at the end of this report, which show the finances to be in sound and satisfactory condition. The statements also contain detailed information respecting the various trust funds, assets and liabilities, and other financial data.

Meetings of the Board.—The Board of Directors has held 10 meeting during the year; nine at Institute headquarters in New York, and one at Cooperstown, N. Y., during the Annual Convention. In order that the membership may keep closely in touch with the administration of the Institute's affairs, a résumé of business transacted at these meetings is published each month in the Institute PROCEEDINGS. This, however, represents only a portion of the business transacted by the Board, as many important matters are considered to which publicity is not given pending their final settlement. Such matters are dealt with in subsequent issues of the PROCEEDINGS under appropriate headings.

Conventions.—The Annual Convention was held in Cooperstown, N. Y. June 23–27, 1913. The total registered attendance was 242, of which 171 were Institute members. Of the 71 guests, 54 were ladies. Twenty-four papers were presented at the six technical sessions. The reduction in the number of papers over the two previous years was favorably commented upon, as it afforded longer time for discussion and eliminated the necessity for parallel sessions.

The success of the first Midwinter Convention, held in New York early in 1913, led the Board to give favorable consideration to a demand for a similar convention this year, which was held at Institute headquarters February 25–27, 1914, under the auspices of the Electric Power Committee. Sixteen papers and reports on the general subject of electric power were presented, several of the reports embodying separate short papers by different authors, each devoted to some subdivision of the main

subject. The total registered attendance was 472, of which 354 were Institute members. A subscription dinner-dance, under the joint auspices of the Institute and the Executive Committee of the Committee on Organization of the International Electrical Congress to be held in San Francisco in 1915, was the only official social function of the convention. About 350 members and guests participated in this event.

The fifth annual Pacific Coast Convention was held in Vancouver, B. C., September 9–11. The arrangements were made and admirably carried out under the auspices of the Vancouver Section. Six technical papers, relating chiefly to industries and operations of interest to engineers on the coast and in the northwest, were presented. The total attendance was 154. Vice-President Lighthipe represented the President, and presided at this meeting.

Other Meetings.—A meeting was held in Philadelphia, Pa., on October 13, 1913, under the auspices of the Philadelphia Section. Three papers were presented and discussed at this meeting, and the total attendance was 204.

A meeting was held in Pittsburgh, Pa., April 9–10, 1914, under the auspices of the Committee on the Use of Electricity in Mines and the Pittsburgh Section. Five papers on the application of electricity in mining were presented, and 191 members and guests attended.

A two-day meeting was held in Washington, D. C., April 24–25, 1914, in cooperation with the American Physical Society. The meeting was conducted on behalf of the Institute by the Electrophysics Committee, with the assistance of the Washington and Baltimore Sections, and the papers presented related more or less to the general subject of electrophysics. The Institute contributed five of the papers presented at the meeting.

In addition to the foregoing meetings, regular monthly meetings have also been held in New York, excepting during the summer months.

The Sections and Branches of the Institute have been exceedingly active, having held more than 500 meetings throughout the country.

During the year, President Mailloux, Honorary Secretary Pope, and Secretary Hutchinson have attended a large number of Institute and Section meetings in various parts of the country.

Future Institute meetings during the present year are being arranged for, as follows: Pittsfield, Mass., May 28–29; Annual Convention, Detroit, Mich., June 23–26, Pacific Coast Convention, Spokane, Wash., September 9–11.

Scientific Lectures.—The wide-spread interest shown by members and non-members in the lectures on radioactivity by Professor E. P. Adams of Princeton University a year ago prompted the Board to authorize the appointment of a special committee on Technical Lectures last fall, through which arrangements were made with Dr. M. I. Pupin, Professor of Electromechanics in Columbia University, New York, to deliver two lectures on the subject of the relation of the electromagnetic theory to the science of electrical engineering of the present day. The lectures were given in New York on April 29 and May 6, 1914. Dr. Pupin's lectures were planned to bring out the points of contact between Maxwell's electromagnetic theory and the ordinary and less broad electromagnetic theory which serves as the foundation of electrical engineering today.

International Electrical Congress.—The Executive Committee of the Committee on Organization of the International Electrical Congress, San Francisco, 1915, which is invested with powers to carry on the work for the general committee, was reorganized during the year with a chairman, a vice-chairman, and nine other members, in order that it could more effectively carry on its work, which has developed considerably during the year. The question of financing the Congress was referred to the Board of Directors for consideration by the committee last fall, and it became necessary to make some adequate provision for funds to be available for this purpose until such time as the committee's income through subscriptions would enable it to finance the Congress independently of the Institute. This was accomplished by the passage of a resolution by which the Institute agreed to underwrite the expenses of the Congress to the extent of $15,000, with the understanding that the Institute is to be reimbursed to the full amount advanced if the Congress proves to be self-supporting, as expected, and is to receive the profits, if any. In agreeing to underwrite the expenses of the Congress, the Board took the view that inasmuch as the project of holding the Congress originated with the Institute, and as, by authority of the International Electrotechnical Commission, the Congress is being conducted under the auspices of the Institute, the responsibility for obligations incurred in connection with it rests upon the Institute. Additional information regarding the Congress may be found in the abstract of the report of the Executive Committee in the following pages.

International Engineering Congress.—This congress is entirely distinct from the Electrical Congress, and is to be held a week after the latter. It is being organized under the auspices of the American Society of Civil Engineers, the American Society of Mechanical Engineers, the American Institute of Mining Engineers, the Society of Naval Architects and Marine Engineers, and the American Institute of Electrical Engineers. The Institute's interest in this congress is limited, on account of its obligations to the Electrical Congress, for which it is solely responsible, and upon the success of which its efforts must necessarily be largely centered. The Institute is, however, heartily in sympathy with the proposed engineering congress, is represented upon its Board of Management, and is actively cooperating in the work of preparation.

Standardization Rules.—One of the most useful and important activities which the Institute has undertaken in recent years, and upon which a very large amount of time and energy has been concentrated during the past year, is the preparation of a revised edition of the Standardization Rules. Credit for this work is due to the Standards Committee, which, after nearly two years of unremitting labor, has practically completed the revision of the rules, and it is expected that the revised rules will be referred to the Board of Directors for formal action at the coming Annual Convention.

Foreign Relations.—The Institute's relations with foreign engineering societies have continued harmonious and cordial. The reciprocal arrangement for the exchange of visiting member privileges with some of the foreign societies still remains in force, and has been availed of to a

considerable extent. The Secretary has issued during the past year a large number of visiting member certificates to Institute members who have gone abroad, and an approximately equal number of certificates from foreign societies has been honored by the Institute.

An important step towards international representation was taken by President Mailloux last August by the appointment, upon authorization of the Board, of representatives of the Institute upon the United States National Committee of the International Illumination Commission, a newly-organized body formed from the International Photometric Commission at a meeting of the latter held for that purpose in Berlin, in August, 1913. In all, ten countries were represented by delegates. President Mailloux unofficially represented the Institute and took a conspicuous part in the proceedings. All of the statutes, resolutions and official documents of the Commission are to be drawn up in the French language, while the national committees may draw up translations which may be published on their own respective responsibilities. Several other American organizations are represented on the U. S. National Committee.

The very friendly relations which have always existed between the American Institute of Electrical Engineers and the Institution of Electrical Engineers of Great Britain have become more cordial than ever during the last year, through the personal efforts of their presidents, prior to and since their meeting at Berlin in August, 1913, as members of the official delegations from their respective countries to the meetings of the International Illumination Commission and of the International Electrotechnical Commission.

In accordance with arrangements previously made by letter and by cable a special conference of prominent members of the A. I. E. E. and the I. E. E. took place at London, in August, 1913, prior to the Berlin meetings. The purpose of this conference was to exchange and compare views, adjust and reconcile policies and programmes, and, in general, to secure coöperative, concerted action between the two countries in regard to electrical standardization and various cognate matters, and on questions of mutual interest to both. This conference was most effective in promoting good feeling, and in stimulating the desire for coöperation between the two bodies. It paved the way for an "*entente cordiale*" which, a few days later, at Berlin, produced telling results, by making the representatives from England and the United States work together in most satisfactory and effective manner, their joint efforts and influence having proved quite preponderating both in the organization of the I. I. C. and in the meetings of the I. E. C.

The desire for continued and systematic coöperation between the A. I. E. E. and the I. E. E. having already found expression at London and at Berlin, and the advantages thereof having become manifest since then, the matter was studied further on both sides and arrangements satisfactory to both sides were agreed upon. Formal action in carrying out these arrangements was taken by President Mailloux last February, when he obtained the authority of the Board to suggest to the Institution of Electrical Engineers that a Joint Conference Committee composed of representatives of the Institution and the Institute be organized to deal

with matters regarding which concerted action between the standards committees of the two bodies might be desirable, and, if the suggestion was received favorably, to appoint the Institute's representatives. The Institution promptly accepted the invitation of the Institute to participate in the formation of such a joint committee.

Committees and Departments.—Upon entering into his administration of the Institute's affairs in August, 1913, President Mailloux, with the sanction of the Board, reorganized the technical committees and divided the work of the Institute into six departments, with a vice-president and manager at the head of each department as Councillor and Vice-Councillor. The features of the plan were fully described in the September, 1913, PROCEEDINGS.

The Standards Committee was considerably enlarged so as to permit the appointment of sub-committees of a suitable number.

Three new committees were appointed; namely, Electric Power, Electrically Propelled Vehicles, and Prime Movers. The Electric Power Committee was organized to cover a very broad field, and was divided into sub-committees on Power Stations, Power Generation, Protective Apparatus, Transmission, Distribution, Economics, and Engineering Data, each sub-committee having its own chairman and membership.

Committee Reports.—The following abstracts of the reports submitted by the chairmen of various permanent Institute committees give an outline of the activities of these committees. Much important work has also been accomplished by temporary committees appointed during the year for specific purposes; also by delegates of the Institute to meetings of other technical organizations and by representatives upon various boards, commissions, and other local and national bodies.

Sections Committee.—In accordance with the custom of previous years, the activities of the various Sections and Branches of the Institute are shown briefly in tabular form below:

	Year Ending						
	May 1 1908	May 1 1909	May 1 1910	May 1 1911	May 1 1912	May 1 1913	May 1 1914
Sections							
Number of Sections	21	24	25	25	28	29	30
Number of Section meetings held....	141	169	187	208	231	244	233
Total attendance...	7476	16,427	16,694	15,243	19,800	22,825	22,626
Branches							
Number of Branches	22	26	31	36	42	47	47
Number of Branch meetings held.....	143	198	237	255	281	357	306
Attendance.....	4128	8,443	10,255	10,714	10,255	11,808	11,617

One new Section has been formed within the last year, at Panama. Judging from the notices that have come from the new Section, it has had a highly successful inauguration.

The Pacific Coast membership have not as yet held their annual convention, but it is held over until September, thereby making it the first of the Institute meetings which will occur in the next administrative year. This will be the sixth of these Pacific Coast conventions which have been held among the six Pacific Coast Sections. The convention this year will be held in Spokane, Wash., September 9, 10 and 11.

These conventions have been highly influential in maintaining the solidarity of the Institute membership on the Pacific Coast.

The Sections and Branches continue to maintain the important place in Institute activities that they have maintained since their inauguration twelve years ago.

Meetings and Papers Committee.—The Meetings and Papers Committee has had general supervision of the arrangements for the Institute meetings and conventions held throughout the country during the year. In providing the program for these meetings the committee has had the coöperation and assistance of various other Institute committees. The chairman of the committee contributing the paper for discussion at a meeting has usually presided at the technical session at that meeting.

The committee is now making preparation for the Annual Convention, which is to be held in Detroit, Mich., June 23-26, 1914. The committee is pursuing the same policy as last year in limiting the number of papers to be presented, having found this a great advantage, as it affords a longer time for discussion and eliminates the necessity for parallel sessions.

New York Reception Committee.—The New York Reception Committee has arranged for the smokers which have been held at Institute headquarters in connection with the monthly meetings. These smokers have been supported entirely by voluntary contributions from members residing in and near New York.

Standards Committee.—The membership of the Standards Committee, as appointed last year, has been larger than heretofore, so as to permit of the division of the committee into sub-committees on specific subjects. Six sub-committees have been created, to deal with the subjects of Rating, Telegraph and Telephone Standards, Railroad Standards, Nomenclature and Symbols, Cables, and Rating and Testing of Control Apparatus. Each sub-committee has been presided over by a chairman.

The committee, as a whole, has bent its energies during the year to producing a new edition of the Standardization Rules. Since the last edition was issued in 1911 many rules in it have ceased to be useful, and should be superseded. A large amount of material for the new edition was laid before the Institute in the papers read at the New York Midwinter Convention of February, 1913. Since that date the Standards Committee has been actively engaged in drawing up the proposed new rules and in circulating the proposals for discussion. Preliminary drafts of sections of the proposed new rules were printed in December, 1913, January, February, March and April, 1914. Many of these drafts have been extensively circulated, especially those prepared by the sub-committee on Rating. The sub-committees have successively discussed and modified these drafts in local meetings attended by specialists from different parts of the country.

The meeting of the whole committee in April, at the Institute rooms,

lasted two full days. The latest revision is now being prepared for further distribution, and for final discussion at a meeting in June. It is expected that the committee will then be able to submit the new edition to the Board of Directors at the Annual Convention.

Code Committee.—The Code Committee was represented by its chairman at a Conference on Fire Prevention held in Philadelphia in October, 1913, under the auspices of the Philadelphia Fire Prevention Commission. The outcome of the conference was that the work which it was expected would be handled by the Commission is to be taken care of by the Public Policy Committee of the National Board of Fire Underwriters.

The chairman of the committee also represented the Institute at the biennial meeting of the Electrical Committee of the National Board of Fire Underwriters held in Boston in April. At this meeting the committee appointed to reconstruct Rule 13, dealing with outside construction, decided to postpone definite action until the result of the work of the joint committee of the American Railway Association on the joint use of poles is known.

Library Committee.—In accordance with Section 24 of the by-laws of the Institute, the Library Committee begs leave to submit herewith its report for the fiscal year ending April 30, 1914, showing the general condition of the library, and including the names of all donors to it.

The administration of the library's affairs by the Library Board, which was organized for this purpose with the approval of the founder societies in February 1913, has proved very satisfactory, and the Board has accomplished a considerable amount of constructive work during the year.

One of the most important matters to claim the attention of the Board was the general question of financing the library. The subject was brought up for discussion at a meeting held on December 4, 1913, and resulted in the appointment of a special committee consisting of the secretaries of the three founder societies to formulate a plan for the apportionment of expenditures and appropriations for the library, and to make specific recommendations for the classification of library accounts.

This committee submitted its report to the Library Board on February 5, 1914, and on March 26, 1914, the plan recommended by the committee was formally adopted by the Board of Trustees of the United Engineering Society. The principal features of the plan are as follows:

1. That a permanent Finance Committee of three members of the Library Board, one representative from each society, be created, each member being designated by the Library Committee of the society which he represents. This committee to have supervision of the library expenditures under the direction of the Library Board.

2. That the United Engineering Society bear one-quarter of the operating expenses of the library, dating from January 1, 1914, the remaining three-quarters to be borne equally by the three founder societies.

3. That all purchases of books, periodicals and binding be made by the librarian upon the authorization of the Library Committee of the founder society concerned, or in the case of the United Engineering Society, by the Finance Committee of the Library Board, and that the

cost of such books, periodicals and binding be borne in each case by the society concerned.

4. That the research work carried on under the direction of the librarian be made, as far as possible, self-supporting.

Under this plan the United Engineering Society shares in the operating expenses of the library, which heretofore were borne entirely by the three founder societies.

The library now contains over 54,000 volumes, and about 1,600 complete and partial sets of periodicals. Over 800 periodicals are received currently.

Data, which shall form the basis of a list of the sets of technical periodicals in the various libraries of New York City, have been obtained and the work of compiling this list is now progressing.

The research department has developed considerably during the year. Over a thousand questions have been received requiring research, and a large number of photographic reproductions and reference lists have been sent to out-of-town clients, both here and abroad, thus extending the facilities of the library to every part of the world. The fees for research work have been slightly increased, with a view to making this department self-supporting.

Statistical information concerning the library and its use during the year, including a list of donors, is given in the following tables.

DONORS

May 1, 1913—April 30, 1914

ADAMS, E. D	6
AMERICAN ELECTRIC RAILWAY ASSOCIATION	14
AMERICAN ELECTROCHEMICAL SOCIETY	3
AMERICAN INSTITUTE OF CONSULTING ENGINEERS	1
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS	1
AMERICAN MINING CONGRESS	1
AMERICAN RAILWAY ASSOCIATION	1
AMERICAN SCHOOL OF CORRESPONDENCE	2
AMERICAN TELEPHONE AND TELEGRAPH COMPANY	4
ARGENTINE SOCIAL MUSEUM	1
ARNOLD, B. J	6
ASSOCIATION OF IRON AND STEEL ELECTRICAL ENGINEERS	1
BARBIERI, M	1
BISHOP, L. W	1
BRAMMER, J. C	1
BROOKLYN ENGINEERS CLUB	1
CALDWELL, EDWARD	2
CARNEGIE LIBRARY OF PITTSBURGH	1
CHICAGO COMMITTEE ON GAS, OIL AND ELECTRIC LIGHT	1
CITY AND GUILDS ENGINEERING COLLEGE	1
CLEVELAND ENGINEERING SOCIETY	1
CONGRESO CIENTIFICO (1° PAN AMERICANO)	2
CONGRESSO INTERNAZIONALE DELLE APPLICAZION ELETTRICHE	1
CROCKER, FRANCIS B	5
DELAWARE COLLEGE	1

DEPARTMENT OF TERRESTRIAL MAGNETISM 1
ELECTRIC RAILWAY JOURNAL 1
ELECTRICAL WORLD 1
ELECTRO-TECHNICAL LABORATORY, TOKYO 2
ELECTRO-TECHNICAL LABORATORY, DEPT. OF COMMUNICATION, TOKYO 2
ENGINEERS' CLUB OF PHILADELPHIA 1
FORD, BACON & DAVIS 1
FOWLE, F. F 2
FOWLER, C. P 1
FRANKLIN INSTITUTE 1
GENERAL RAILWAY SIGNAL COMPANY 1
GAUTHIER-VILLARS 2
HAMMER, WILLIAM J 1
HERMANN ET FILS 2
HUTCHINSON, F. L 1
ILLUMINATING ENGINEERING SOCIETY 1
INSURANCE SOCIETY OF NEW YORK 1
IOWA ENGINEERING SOCIETY 1
JANECKE 1
JONES, R. M 1
JOSEPH DIXON CRUCIBLE COMPANY 1
KANSAS ENGINEERING SOCIETY 1
KENNELLY, A. E 4
KIRCHGASSER 1
KNOWLES, EDWARD R 57
KOWALEUKOFF, W 3
LLOYD'S REGISTER OF SHIPPING 1
LOS ANGELES EXAMINER 1
LUDIN, ADOLF 2
LUMIERE ELECTRIQUE 1
MARYLAND PUBLIC SERVICE COMMISSION 1
MASSACHUSETTS BOARD OF GAS AND ELECTRIC LIGHT COMMISSIONERS 1
MASSACHUSETTS INSTITUTE OF TECHNOLOGY 1
MAYER, WM 6
MINISTERIO DA VIAGAS E OBRAS PUBLICAS, BRAZIL 2
MINISTERO DELLE POSTE E DEI TELEGRAFI 1
MUNICIPAL ENGINEERS OF THE CITY OF NEW YORK 1
NATIONAL ELECTRIC LIGHT ASSOCIATION 1
" " " " BOSTON SECTION 1
NATIONAL FIRE PROTECTION ASSOCIATION 5
NEW ORLEANS SEWERAGE AND WATER BOARD 1
NEW YORK (CITY) BOARD OF TRADE 1
NEW YORK (CITY) BOARD OF WATER SUPPLY 3
NEW YORK (CITY) DEPARTMENT OF WATER SUPPLY, GAS AND ELECTRICITY 1
NEW YORK (STATE) DEPARTMENT OF LABOR 4
NEW YORK (STATE) PUBLIC SERVICE COMMISSION 1
NORSA, RENZI 1

OESTERREICHISCHER INGENIEUR UND ARCHITEKTENVERE N.	2
PENROSE, CHARLES	1
PIERCE, A. L.	2
POLYTECHNIC INSTITUTE OF BROOKLYN	4
PREFECTURE DE LA SEINE	1
PULLIGNY, L. DE	1
REED, HENRY D	1
SAINZ, J.	1
SCHOOL OF ENGINEERING OF MILWAUKEE	1
SIMON, ARTHUR	1
SOCIETY FOR THE PROMOTION OF ENGINEERING EDUCATION	1
SOCIETY OF CHEMICAL INDUSTRY	1
SOUTHWESTERN ELECTRICAL AND GAS ASSOCIATION	2
STREET RAILWAY ASSOCIATION OF THE STATE OF NEW YORK	1
TELEPHONE PIONEERS OF AMERICA	1
THOMPSON, S.	1
ULISSE DEL UNONO	1
UNDERWRITERS LABORATORIES, INC	1
U. S. BUREAU OF NAVIGATION, DEPT. OF COMMERCE	1
U. S. BUREAU OF STANDARDS	1
U. S. DEPARTMENT OF AGRICULTURE	4
U. S. WAR DEPARTMENT	1
D. VAN NOSTRAND COMPANY	4
VERBAND DEUTSCHER ELEKTROTECHNIKER	1
WEAVER FUND	1
WEIN, SAMUEL	1
WESTERN UNION TELEGRAPH COMPANY	1
WOODBURY, C. J. H.	1

Summary of Accessions

May 1, 1913—April 30, 1914

Donors	185
Exchange	170
Purchase and old material	122
Total accessions	477

Statistics of Library May 1, 1914

Source	Vols.	Pamphlets	Valuation
Report of May 1, 1913	16,843	1652	$34,432.75
Purchase	109	1	218.25
Gifts and exchanges	318	37	645.25
Old material accessioned	12		24.00
	17,282	1690	$35,320.25

LIBRARY ATTENDANCE

	Day	Night	Total
May 1913	793	213	1,006
June "	579	142	721
July "	652	closed	652
August "	612	79	691
September "	715	197	912
October "	894	212	1,106
November "	856	235	1,091
December "	1,037	286	1,323
January 1914	1,115	302	1,417
February "	949	293	1,242
March "	984	339	1,323
April "	936	309	1,245
Total May 1913-April 1914	10,122	2607	12,729
Total May 1912-April 1913	7,667	2280	9,947

In the following table are given figures for the total valuation of the library property, no allowance having been made for depreciation:

Books	$35,320.25
Stacks	1,761.05
Furniture, catalogue cases, etc.	376.00
Wheeler cases	930.00
	$38,387.30

The following tabulation gives the state of the accounts from which the Library Committee is entitled to draw:

MAILLOUX ENDOWMENT FUND ($1,000)

(Proceeds for the maintenance of specific sets of periodical publications).

Balance May 1, 1913	$77.55	Expended	$26.75
Interest	45.00	Unexpended	95.80
	$122.55		$122.55

INTERNATIONAL ELECTRICAL CONGRESS OF ST. LOUIS, 1904, FUND.

(Proceeds available for the purchase of non-American international electrical literature).

Invested in New York City 4½% Bonds	$2268.00
Additions to the Funds	81.00
Total Fund	$2349.00

Balance on hand May 1, 1913	$395.24	Expended	0.00
Interest	90.00	Unexpended	485.24
	$485.24		$485.24

During the year the General Library Fund, amounting to $284.92, and the Weaver Fund, amounting to $6.69, were expended for the purchase of books for the library, and therefore these two accounts do not

appear in the statement given above, nor are these amounts included in the record of expenses given below.

INSTITUTE EXPENSES ON ACCOUNT OF LIBRARY.

Share of salaries of librarian, assistants, cataloguer and desk attendant (one-third from May 1, 1913 to December 31, 1913, and one-fourth for remainder of year ending May 1, 1914)	$2600.40
Share of library's supplies, etc.	137.02
*Books and periodicals	150.18
Insurance	88.21
Binding	334.85
	$3310.66

Respectfully submitted,

F. L. HUTCHINSON
F. B. JEWETT
MALCOLM MACLAREN
W. I. SLICHTER
SAMUEL SHELDON, *Chairman.*

Railway Committee.—The Railway Committee has endeavored to make progress in getting comparisons of actual equipment and operating costs characteristic of the various direct-current and single-phase electrical installations connected with trunk line traffic, but thus far has been unsuccessful, because, while some of the officials concerned have been willing to make the necessary exhibits, they have found themselves unable to do so without the coöperation of all concerned. Efforts to this end have therefore been deferred for the present.

Electric Illumination Committee.—This committee was not appointed until November last, by which time the Institute's work for the administrative year was well under way. The committee has held one meeting and has had considerable correspondence, including negotiations with the Illuminating Engineering Society with regard to joint work and obtaining papers on the subject of illumination for the Annual Convention and later meetings of the Institute.

Electric Power Committee.—The Electric Power Committee has been principally engaged with the formation of its plans for the development and holding of the Midwinter Convention. It is anticipated that during the remainder of the year an outline will be prepared of the standardization work which can be desirably handled by the committee and of the specifications which may be outlined by it. Preparations are also being made to take care of one session of the Annual Convention in Detroit.

The activities of the sub-committees on Power Stations, Power Generation, Transmission, Distribution, Economics and Engineering Data are covered in the following abstracts.

Power Stations Sub-Committee.—The Power Stations Committee held many meetings in Boston, which were generally limited to those members residing in Boston and its vicinity, and it also had considerable correspondence with distant members, with the object in view of outlining the duties of the committee and carrying them out efficiently. The com-

*To obtain the total expenditures for books for the year, the amounts expended from the General Library Fund and the Weaver Fund should be added to this sum, thus making the total expenditures for books $441.79.

mittee took the responsibility for one of the sessions of the Midwinter Convention in New York in February, and provided papers for that session.

Power Generation Sub-Committee.—Under the auspices of this committee there was presented at the Midwinter Convention in New York a paper by Dr. Cary T. Hutchinson, on *The Economical Capacity of a Combined Hydroelectric and Steam Plant.*

Transmission Sub-Committee.—The Transmission Committee provided the papers for one of the sessions at the Midwinter Convention in New York in February. The principal paper consisted of a general report comprising data and records of experience contributed by the various members of the committee. Appended to the report were four short articles all relating to the general subject of transmission.

Distribution Sub-Committee.—The Distribution Committee prepared a report with nine appendixes, each covering a specific branch of electrical distribution. The report proper referred to some of the newer and larger general problems and the tendencies in generalized distribution. The report and appendixes, covering practically the entire field of electrical distribution, were presented and discussed at the Midwinter Convention.

Economics Sub-Committee.—The Economics Committee has concentrated its energies upon an effort to arrive at a proper method for recording power costs. The object to be attained is to record these costs so that the results will permit a true comparison of stations operating under different circumstances.

Engineering Data Sub-Committee.—The Engineering Data Committee, in cooperation with the Handbook Committee and the Electric Power Committee, provided the program for one session at the recent Midwinter Convention. The committee has in hand, and now has revised and ready for approval, the model or skeleton high-tension insulator testing specification which was prepared last year by the High-Tension Transmission Committee. It is believed that this specification will be found of considerable value in an educational way and in the establishment of uniformity in practise in insulator tests. The committee has also been continuing the collection of data on high-tension plants which was initiated last year, and now has in hand reports from some 20 companies, most of them containing valuable material. These are being analyzed and it is expected that the analysis will be completed for the Annual Convention. The committee is also trying out the plan of sending circular letters to a selected list of engineers asking for their experience or practise in regard to some particular question of engineering interest, usually at the request of some member wishing information on that particular topic. Such pertinent replies as are received are embodied in a circular letter and sent to the appropriate list of members.

Industrial Power Committee.—This committee was not appointed until late in October, at which time the schedule of regular meetings for the year had been practically decided upon. Consequently, the committee has concentrated its efforts towards arranging for papers to be presented at the Industrial Power session at the Annual Convention in Detroit in June. It is hoped that these plans will result in a satis-

factory meeting. The committee expects to arrange an exhibit of moving pictures of the iron and steel industry for the Annual Convention.

Telegraphy and Telephony Committee.—The Telegraphy and Telephony Committee held no meetings during the year, owing to the wide geographical distribution of its membership. Under arrangements with the Meetings and Papers Committee it accepted the responsibility for the program of the Institute meeting held in New York on March 13, 1914. The Institute of Radio Engineers was invited to participate in this meeting. Three papers were presented; one dealing with railway telephone and telegraph practise, another with a study of telephone traffic in automatic systems, and the third with long-distance radio transmission.

The chairman had considerable correspondence with the members of the committee in regard to the collection and compilation of engineering data in the allied fields of telegraphy and telephony. A number of proposals were advanced by certain members of the committee, and these were submitted to the whole committee for discussion, but no decisive action resulted.

Electrochemical Committee.—The work of the Electrochemical Committee for the past year has been largely devoted to attempts to obtain suitable papers on electrochemistry treated from an engineering viewpoint. Owing to the scattered geographical distribution of its members it has been necessary to carry on the work through correspondence. Three papers were promised during the year, of which one will be presented at the Annual Convention. The remaining two papers are nearly completed and are definitely promised for next season and may be available in the fall.

The committee has also considered the question of collecting technical data in the electrochemical field with a view to collating this for publication under the auspices of the Institute, in line with similar work which is being carried on by several of the other technical committees. Many difficulties have been found in the way of this work, however, and no actual data were collected during the year. One feature that appears in the way of collecting engineering data relating to electrochemistry is the fact that some of the electrochemical industries have not been standardized to a sufficient extent to justify the standardization of the engineering data relating to these industries. Further, such data as the ordinary chemical and electrochemical constants would seem to be more properly collected in handbooks and textbooks, while new data of this kind would seem to be more properly collected by the Electrochemical Society. This society has a committee on electrochemical standards and units.

Electrophysics Committee.—The work of the Electrophysics Committee has been directed (1) to the securing of papers on subjects relating to the physical theory underlying electrical engineering, (2) to the stimulation of interest in experimental research, and (3) to the arrangement of a joint meeting of the Institute and the American Physical Society.

Up to the present time 10 papers have been considered. Five of these were presented at the Washington meeting, April 24 and 25, two are under consideration for the Annual Convention, and two have been rejected as unsuitable. Promises have also been received of two additional papers.

Through correspondence the committee has continued its efforts to

secure a list of promising subjects for research. So far the results of this attempt have not been numerous, but it is hoped that by continued effort in this direction valuable material may eventually be collected.

The committee arranged the Institute meeting held in Washington April 24 and 25 in coöperation with the American Physical Society. The coöperation of the National Bureau of Standards and the Baltimore and Washington Sections was also secured. Arrangements were made for an interesting exhibit of measuring instruments and other apparatus relating to electrical engineering.

Committee on Use of Electricity in Mines.—During the past year the committee has given considerable attention to the question of regulations for electrical installations in mines. After a study had been made of the situation it was decided that it would be desirable to obtain a discussion of mining regulations from individuals interested in this work. There is no recognized standard for electrical work in mines, and on account of the increasing importance of this work it was considered that some standardization is desirable. A two-day meeting of the Institute was held in Pittsburgh on April 9 and 10, at which various European and American mining codes were discussed. In addition a number of papers were read which produced an interesting exchange of ideas. It was suggested that the subject of electrical installation in mines should receive attention from the committee for 1914-1915, with the object of obtaining joint action with other national societies toward the formation of a set of rules meeting with the approval of mining and electrical engineers, which could be used as a basis for standardization and future legislation by state governments.

Committee on Use of Electricity in Marine Work.—This committee has provided the two papers which will be presented at the New York meeting on May 19. These are, *Electricity the Future Power for Steering Vessels*, and *The Future of Electric Heating and Cooking in Marine Service*. The committee has held two meetings during the year and steps have been taken toward the formulation of rules covering electrical installations on shipboard, and the collection of data showing present good practise in marine installations.

Committee on Electrically Propelled Vehicles.—In view of the rapid growth in the use of electric vehicles for both pleasure and commercial purposes it appeared advisable to have an Institute Committee on Electrically Propelled Vehicles. The committee has held only one formal meeting, but the chairman has been in communication with the various members of the committee throughout the year. The general opinion of the members of the present committee is that the committee should confine its attention to the engineering features involved in the design and use of electric vehicles, and that questions of standardization of equipment and parts should be referred to the Standardization Committee of the Electric Vehicle Association of America.

At the request of the chairman of the Standardization Committee of the Electric Vehicle Association of America, the Committee on Electrically Propelled Vehicles has requested the Standards Committee of the Institute to approve the standard charging plug adopted by the Associa-

tion, and has also requested the Standards Committee to endeavor to secure the adoption of this plug by the U. S. National Committee of the International Electrochemical Commission.

Committee on Records and Appraisals of Property.—This committee has decided that its efforts this year should be directed chiefly to formulating, as far as possible, a statement of the general principles which should underlie the production of correct appraisals and records of properties, and that it would be better not to attempt to lay more than a basic foundation upon which next year's committee can work.

Prime Movers Committee.—The Prime Movers Committee is now engaged on a report which it is hoped will be presented at the Annual Convention, covering the present status of the art of prime movers. This report will not only cover the relative efficiencies, but also the economics of the situation.

Educational Committee.—The Educational Committee planned to prepare a report dealing particularly with the development of more effective means of utilizing existing institutions for vocational training. The committee has been in correspondence with the secretaries of the Sections of the Institute, and individual members of the committee have under way special studies, all bearing on the same general subject. The report is nearing completion, but it will not be possible to present it at the Annual Convention as it was hoped could be done, and therefore it is now planned to refer it to next year's committee.

Committee on Technical Lectures.—In accordance with suggestions received at the time of its appointment, the Committee on Technical Lectures arranged for two lectures on the subject of "The Electromagnetic Theory and Its Relation to the Science of Electrical Engineering of the Present Time," by Dr. M. I. Pupin, Professor of Electromechanics at Columbia University. These lectures were given in New York on April 29 and May 6, and were largely attended by Institute members and others.

The committee has considered the subject of arranging for representatives of the Institute to deliver popular lectures on engineering subjects in coöperation with the boards of education of various cities. It is the sentiment of the committee that it is desirable that this work should be undertaken next year.

Editing Committee.—Twelve numbers of the PROCEEDINGS have been published under the auspices of the Editing Committee since April 30th, 1913; the total number of pages being practically the same as for the past two years. During the past year the committee adopted the policy of cutting down the discussions before sending the stenographer's reports to the various speakers for revision. By this means the length of discussion is indicated by the Editing Committee in advance, and considerable correspondence in regard to condensation of discussion has thereby been eliminated. This practise has apparently proved equally satisfactory to the authors and the Editing Committee. During the past year the separate pages for the titles and abstracts of papers in the PROCEEDINGS have been eliminated and the abstract included on the title page as part of the paper. The typographical style of the PROCEEDINGS has thereby been improved and a saving of over $1,000 effected by the elimination of two pages for each of the papers published. The change

in the weight and character of the paper on which the 1912 issue of the TRANSACTIONS was printed permitted this volume to be issued in two parts instead of three as in the previous year, thereby effecting considerable saving in shelf space for the volume as well as a substantial saving in cost of publication.

Indexing Transactions Committee.—The Index to the TRANSACTIONS covering the period from 1884 to 1910 was completed last fall. Volume II, covering the years 1901 to 1910, was issued in September, and Volume I, covering the years 1884 to 1900, was issued a few months later. Announcements that the volumes were ready and would be sent gratis to any Institute member desiring them, were published in the September and December 1913 issues of the PROCEEDINGS, together with full information regarding the index, and the volumes have since had a wide distribution.

The index consists of two separate parts, each intended for a distinct purpose.

1. An index of papers in which they are classified in natural groups and arranged chronologically in each group. In each case the title and author are given, with a brief synopsis of the contents of the paper, and the names of those who took part in the discussion. Reference is given to volume number, year and page.

2. A topical index of specific data and information arranged alphabetically. This part of the index furnishes a guide to all the information contained in the TRANSACTIONS, and is grouped naturally under nouns and phrases, followed by modifying adjectives and sub-classes, all arranged alphabetically.

An index arranged on a similar plan, covering the matter contained in the papers and discussions during the year, is now published in each annual volume of the TRANSACTIONS, beginning with 1911.

Public Policy Committee.—The Public Policy Committee has held three meetings to consider and report upon matters referred to it by the President and Board of Directors; namely, the matter of sending a memorial to the President of the United States urging the appointment of one or more engineers on the Interstate Commerce Commission; to consider the continuation of the Institute's representation on the Advisory Board of the National Conservation Congress; and, to consider the invitation from the Secretary of the Interior, to confer with him on the subject of proposed legislation to govern the issue of permits for hydroelectric development on the public domain.

Patent Committee.—At the request of the Patent Committee a meeting of the Public Policy Committee was called in April to consider certain information which had been brought to the attention of the chairman of the Patent Committee in regard to the U. S. Patent Office. As a result of the meeting the Public Policy Committee recommended the appointment of a special committee of the Institute to appear before the House Committee on Appropriations, in Washington, and urge the inclusion in the Sundry Civil Bill of the sum requested by the Hon. Thomas Ewing, Commissioner of Patents, for the preparation of plans for a new Patent Office.

Committee on Relations of Consulting Engineers.—This committee has kept in touch with the practise and experience of the American In-

stitute of Consulting Engineers in the use of the schedule of recommended charges adopted by that Institute, and has collected valuable data relating to the regulations governing the fees of architects and consulting engineers as adopted in certain foreign countries.

Committee on Code of Principles of Professional Conduct.—This committee has had nothing referred to it for action during the year. The code as adopted two years ago has been used as a basis by other societies and organizations for the formulation of codes of ethics or principles of professional conduct for themselves.

Constitutional Revision Committee.—As reported to the Board last January, the general sentiment of the Constitutional Revision Committee was that the best interests of the Institute would be served by not initiating any amendments to the Constitution this year. There are a number of minor points in the Constitution which could be made clearer or more consistent. Such changes might best be brought to the attention of the membership for vote when important constitutional changes are also to be voted upon.

It is thought by the committee that the present Constitution goes too much into detail with reference to certain matters, particularly concerning committees. The duties of certain committees, presumably the Executive Committee, the Board of Examiners, the Tellers, Finance, Sections, Editing, and Meetings and Papers Committees, should be dealt with in the Constitution. The other committees might be more properly regulated by the by-laws.

U.S. National Committee, International Electrotechnical Commission.—The Commission held a meeting in Berlin in September, 1913. The U. S. National Committee was represented at this meeting by President Mailloux and Messrs. Bell, Hobart, Kennelly, and Sharp. An advance report of the meeting was prepared by the Secretary of the American delegation and printed in the Institute PROCEEDINGS for November 1913, pp. 2148-2162.

Since the date of the last committee report in May 1913 the following publications have been issued by the Central Office:

June 1913, No. 23	List of Members
June 1913, No. 24	Fourth Annual Report to December 1912
Nov. 1913, No. 25	Résumé of Meetings of Special Committees held in Berlin, September 1913.
Dec. 1913, No. 26	Résumé of Meetings of Special Committees held in Berlin, September 1913.
Jan. 1914, No. 27	International Symbols Adopted at Berlin, September 1913.
Mar. 1914, No. 28	International Standard of Resistance for Copper.

Several meetings of the committee have been held during the year and communication has been maintained with the other national committees, on various topics, through the Central Office in London.

In many ways the I. E. C. has accomplished and is accomplishing results of widespread benefit. The U. S. National Committee continues to take a prominent and active part in this work as it has in the past.

Committee on Organization of International Electrical Congress.—During the year ending April 30, 1914, the work of organizing the Inter-

national Electrical Congress has taken definite form. Early in the year the Executive Committee of the Committee on Organization was reorganized with a chairman, a vice-chairman and seven members, most of whom are chairmen of sub-committees charged with the responsibility of the proper conduct of certain phases of congress work. An Honorary President and Honorary Secretary of the Congress were also appointed, both of whom are *ex officio* members of the Executive Committee.

President Mailloux also appointed as Honorary Members of the Committee on Organization prominent engineers in foreign countries, bringing the total membership of the committee up to about 335 members.

The Executive Committee has been invested with plenary powers to conduct the organization work on behalf of the committee at large.

A number of important steps were taken by the Executive Committee during the year toward promoting the successful organization of the Congress. Membership fees were fixed at the lowest practicable point, with the object in view of securing the widest possible dissemination of the Congress transactions and the largest practicable membership.

Invitations to subscribe to membership in the Congress were issued beginning about March 1, 1914. These were sent first to Institute members, and are now being issued in European countries. Invitations to present papers before the Congress have been issued to a carefully selected list of approximately 150 engineers in countries other than the United States. Similar invitations will shortly be issued to American engineers. Steps are being taken to secure official governmental representation in the Congress.

The committee reports an encouraging display of interest in the Congress, and the conditions appear propitious for a highly successful and very useful Congress.

Edison Medal.—By the unanimous vote of all of the members of the Edison Medal Committee, the fifth Edison Medal was awarded on December 10, 1913, to Mr. Charles F. Brush, of Cleveland, Ohio, "for meritorious achievement in the invention and development of the series arc lighting system." The presentation will be made during the Annual Convention at Detroit.

Board of Examiners.—The Board of Examiners has held 11 meetings during the year. It has examined and referred to the Board of Directors with its recommendations a total of 1373 applications of all classes. A summary of these is as follows:

Recommended for election to the grade of Associate	685	
Recommended for election to the grade of Member	45	
Recommended for election to the grade of Fellow	3	
Not recommended for election to the grade of Associate	1	
Not recommended for election to the grade of Member	9	
Recommended for enrolment as students	519	1,262
Recommended for transfer to the grade of Member	46	
Not recommended for transfer to the grade of Member	20	
Recommended for transfer to the grade of Fellow	34	
Not recommended for transfer to the grade of Fellow	11	111
Total number of applications considered		1,373

Membership.—The Membership Committee deemed it inadvisable to attempt a membership campaign by direct circulation of literature soliciting new members. It was felt that this work could be carried on to better advantage through the Sections, and accordingly, a circular letter was issued inviting their coöperation. Many of the Sections have active membership committees and all of them are coöperating in advancing the interest of the Institute by obtaining desirable new members. The following table shows the number of members in each grade, the total membership, and the additions and deductions which have been made during the year.

	Honorary Member	Fellow	Member	Associate	Total
Membership, April 30, 1913.	5	316	847	6486	7654
Additions:					
Elected	1	4	42	700	
Transferred		121	264		
Reinstated			6	44	
Deductions:					
Died	1	1	7	28	
Resigned		1	6	138	
Dropped			9	384	
Transferred			110	275	
Membership, April 30, 1914.	5	439	1027	6405	7876

Net increase in membership during the year..... 222

Deaths.—The following deaths have occurred during the year:

Honorary Member.—Sir William H. Preece.

Fellow.—Stephen D. Field.

Members.—Julius C. Calisch, Richard N. Dyer, Edwin J. Houston, Francis W. Jones, F. V. T. Lee, W. D. Marks, W. A. Pearson.

Associates.—L. E. Beilstein, R. E. Bowser, E. A. Byrnes, J. R. Calhoon, M. M. Corbin, C. E. Delafield, R. M. Ferris, E. M. Filine, H. H. Fulton, L. J. Gallagher, P. F. Harbolt, L. D. Hitzeroth, R. M. Hopkins, George R. Kempton, J. A. Kraeuchi, A. W. Lindgren, L. N. Peart, William Pitt, David H. Roberts, A. G. Rodgers, Eugene Romig, Clinton B. Smith, Wilson B. Strong, H. H. Struthers, C. Edgar Titzel, George Westinghouse, C. W. Whitman, Sidney Woodfield.

Total deaths, 37.

Finance Committee.—The following correspondence and financial statements form a complete summary of the work of the Finance Committee for the year.

NEW YORK, May 12, 1914.

BOARD OF DIRECTORS,

American Institute of Electrical Engineers.

Gentlemen:

Your Finance Committee respectfully submits the following report for the year ending April 30, 1914.

During the past year the committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes, and otherwise performed the duties prescribed for it in the Constitution and By-laws. Haskins and Sells, chartered accountants, have audited the Institute books, and their certification of the Institute finances follows.

In company with your Secretary and a member of the firm of chartered accountants, the committee has examined the securities held by the Institute and finds them to be as stated in the accountants' report.

Early in 1913, in consequence of certain extraordinary expenses incurred during the previous year, the Board was obliged to negotiate a loan of $10,000 in order to meet the Institute's current obligations. The note was taken up several months later, when funds began to accumulate through the payment of dues, but it appeared inevitable at the time that a similar condition must arise early in the present year. Such, however, has not been the case; the income from dues has been sufficient to meet all expenditures and to take up the note referred to, without in any way curtailing the Institute's activity. In fact, its field has broadened considerably during the year.

It will be noted that there is a surplus of $14,966.39 for the fiscal year. Of this amount, $3,805.94 is made up of accessions to the Library—volumes and fixtures and to works of art.

A change has been made in the form of the report, which will be particularly noted in Exhibit B, the report for the past fiscal year stating the revenue and the expenses for the year, in place of receipts and disbursements. This change we believe will show more clearly the financial operations than the form previously employed.

It will also be noted that the financial affairs of the Institute are in excellent condition, and there is every reason to anticipate that the coming year will prove equally prosperous, which should enable the Institute to take care of the amount it has underwritten in connection with the International Electrical and International Engineering Congresses, to be held in 1915, without impairment of its invested surplus.

Respectfully submitted,

J. FRANKLIN STEVENS,

Chairman Finance Committee

AMERICAN INSTITUTE OF

GENERAL BALANCE SHEET

EXHIBIT A.

ASSETS.

LAND AND BUILDING:			
Interest in United Engineering Society's Real Estate, No. 25 to 33 West 39th Street:			
Building		$353,346.61	
One-third Cost of Land		180,000.00	
Total Land and Building			$533,346.61
EQUIPMENT:			
Library—Volumes and Fixtures		$38,387.30	
Works of Art, Paintings, etc.		3,001.35	
Office Furniture and Fixtures		10,786.11	
Total Equipment			52,174.76
INVESTMENTS:			
Bonds:			
New York City, 4½%, 1917, Par $8,000.00		$8,362.50	
New York City, 4½%, 1957, Par $22,000.00		23,590.00	
City of Wilmington, Delaware, 4½%, 1934, Par $15,000.00		15,997.50	
Chicago, Burlington & Quincy Railroad Company, 4%, 1958, Par $15,000.00		14,606.25	
Total Investments			62,556.25
WORKING ASSETS:			
Publications entitled "Transactions," etc.		$8,674.25	
Badges		911.15	
Total Working Assets			9,585.4
CURRENT ASSETS:			
Cash		$3,410.26	
Accounts Receivable:			
Members for entrance fees and past dues		9,640.50	
Advertisers		1,564.75	
Miscellaneous		999.15	
Interest Accrued—Investments		831.25	
Interest Accrued—Bank Balances		77.17	
Total Current Assets			16,523.08
FUNDS:			
Land, Building, and Endowmeat Fund:			
Cash	$7,513.54		
Interest Accrued	78.20		
		$7,591.74	
Life Membership Fund:			
Cash	$5,431.91		
Interest Accrued	69.00		
		5,500.91	
International Electrical Congress of St. Louis—Library Fund:			
Cash	$566.24		
New York City Bonds, 4½%, 1957, Par $2,000.00	2,268.00		
Interest Accrued	45.00		
		2,879.24	
MAILLOUX FUND:			
Cash	95.80		
New York Telephone Company Bond, 4½%, 1939	1,000.00		
Interest Accrued	22.50		
		1,118.30	
Total Funds			17,090.19
Total			$691,276.29

ELECTRICAL ENGINEERS

April 30, 1914

Liabilities.		
Bond and Mortgage—United Engineering Society—One-third Interest in Land, 25 to 33 West 39th Street		$54,000.00
Current Liabilities:		
Accounts Payable—Subject to Approval by the Finance Committee	5,561.78	
Interest Accrued on Bond and Mortgage	720.00	
Members' dues paid in advance	814.75	
Entrance fees and dues advanced by applicants for membership	72.00	
Total Current Liabilities		7,168.53
Reserves:		
Land, Building and Endowment Fund	$7,591.74	
Life Membership Fund	5,500.91	
Mailloux Fund	1,118.30	
International Electrical Congress of St. Louis—Library Fund	2,879.24	
Total Funds	17,090.19	
Reserve for Depreciation of Furniture and Fixtures	4,867.78	
Total Reserves		21,957.97
Surplus: Per Exhibit "B"		608,149.79
Total		$691,276.29

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Statement of Income and Profit and Loss

For the Year Ended April 30, 1914

Exhibit B.

Revenue:

Entrance Fees		$4,228.75	
Dues		85,915.63	
Students' Dues		4,245.00	
Transfer Fees		670.00	
Advertising		10,041.92	
Subscriptions		3,061.70	
Sales of "Transactions," etc.		2,408.12	
Badges Sold	$2,104.00		
Less Cost	1,644.81	459.19	
Interest on Investments		2,626.00	
Interest on Bank Balances		316.69	
Exchange		24.94	
Total			$113,997.94

Expenses:

Meetings and Papers Committee:			
Salaries		$4,300.00	
Binding and Mailing Proceedings		4,807.60	
Printing Proceedings		8,504.86	
Engraving Proceedings		1,022.57	
Paper and Cover Paper		5,056.94	
Envelopes		821.12	
Stationery and Miscellaneous Printing		133.47	
General Expense		148.71	
Meetings		6,106.69	
Volume No. 30		3.60	
Volume No. 31		11,892.31	
Total		$42,797.87	
Deduct Increase in Inventory of Publications:			
May 1, 1913	$7,628.25		
April 30, 1914	8,674.25	1,046.00	$41,751.87
Executive Department:			
Salaries		$14,842.00	
General Expense		1,645.17	
United Engineering Society—Assessments		3,375.00	
Express		206.65	
Postage		3,602.62	
Advertising		2,010.95	
Office Furniture and Fixtures		287.72	
Stationery and Miscellaneous Printing		3,600.13	
Year Book and Catalogue		2,687.49	
Interest on Bond and Mortgage		2,160.00	
Interest on Note Payable		18.75	
Engraving		13.06	34,449.54
Forward			$76,201.41
Revenue—(Forward)			$113,997.94

REVENUE—(Forward)		$113,997.94
EXPENSES—(Forward)		76,201.41
Sections Committee:		
Section Meetings	$3,651.32	
Branch Meetings	224.58	
Delegates Convention Expenses	1,613.36	
Salary and Traveling Expenses, Honorary Secretary	4,353.78	
Salaries, New York Office	2,268.00	
Stationery and Printing, New York Office	674.22	
Express on Advance Copies	61.56	12,846.82
General:		
Library	$3,310.66	
Indexing "Transactions,"	1,832.21	
International Electrotechnical Commission	275.54	
Finance Committee	150.00	
Standards Committee	612.60	
President's Special Appropriation	228.30	
Annual Function	365.00	
Law Committee	500.00	
International Engineering Congress, 1915	875.00	
International Illumination Committee	100.00	
Membership Committee	4.25	8,253.56
Add:		
Increase in Accounts Payable—Subject to Approval by the Finance Committee, Undistributed at:		
May 1, 1913	$4,335.91	
April 30, 1914	5,561.78	1,225.87
Total Expenses		$98,527.66
NET REVENUE		$15,470.28
PROFIT & LOSS CREDITS:		
Accessions:		
Library Volumes and Fixtures	$3,460.94	
Works of Art	345.00	
Total		3,805.94
GROSS SURPLUS FOR THE YEAR		$19,276.22
PROFIT & LOSS CHARGES:		
Uncollectible Dues Written Off	$3,180.00	
Reservation for Depreciation of Furniture and Fixtures	1,129.83	
Total		4,309.83
NET SURPLUS FOR THE YEAR		$14,966.39
SURPLUS, MAY 1, 1913		593,183.40
SURPLUS, APRIL 30, 1914		$608,149.79

NEW YORK, May 11, 1914.

American Institute of Electrical Engineers,
33 West 39th Street, New York.

Dear Sirs:

Pursuant to engagement, we have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1914, and submit herewith our certificate and the following described exhibits:

EXHIBIT

"A"—General Balance Sheet—April 30, 1914.

"B"—Statement of Income and Profit & Loss for the Year Ended April 30, 1914.

Yours truly,
(Signed) HASKINS & SELLS
Certified Public Accountants.

CERTIFICATE

We have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1914, and

WE HEREBY CERTIFY that the accompanying General Balance Sheet properly sets forth the financial condition of the Institute on April 30, 1914, that the Statement of Income and Profit & Loss for the year ended on that date is correct, and that the books of the Institute are in agreement therewith.

(Signed) HASKINS & SELLS
Certified Public Accountants.

NEW YORK,
May 11, 1914.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

STATEMENT OF CASH RECEIPTS AND DONATIONS FOR DESIGNATED PURPOSES. ALSO DISBURSEMENTS, FOR THE YEAR ENDED APLIL 30, 1914.

EXHIBIT C.

RECEIPTS AND DONATIONS:	
Land, Building and Endowment fund—Donations, Interest, etc.	$398.22
Life Membership Fund	362.92
International Electrical Congress of St. Louis Library Fund Donations, and Interest	94.15
Mailloux Fund, Interest	45.00
General Library Fund, Interest	6.97
Total	$907.26
DISBURSEMENTS:	
Life Membership Fund	$456.88
General Library Fund	284.92
Mailloux Fund	26.75
Weaver Fund	6.69
Total	775.24

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the past eight years.

Year ending April 30	1907	1908	1909	1910	1911	1912	1913	1914
Membership, April 30, each year	4521	5674	6400	6681	7117	7459	7654	7876
Receipts per Member	$12.21	$13.01	$13.21	$13.35	$13.37	$13.19	$13.45	$14.08
Disbursements per Member	11.62	11.73	10.49	12.03	11.03	12.44	15.57	12.86
Credit Balance per Member	$ .59	$1.28	$2.72	$1.32	$2.34	$ .75	*$2.12	$1.22

*Deficit.

Respectfully submitted for the Board of Directors,

F. L. HUTCHINSON, *Secretary.*

New York, May 19, 1914.